# The mirror box illusion

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**The 'mirror box' illusion:**
**Manipulation of visual information during bimanual coordination in children with and without spastic hemiparetic cerebral palsy**

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The research presented in this thesis was carried out at the Research Institute MOVE, Faculty of Human Movement Sciences, VU University, Amsterdam, The Netherlands in collaboration with the Institute for Biomedical Research into Human Movement and Health, Department of Science and Engineering, Manchester Metropolitan University, Manchester, United Kingdom.

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# THE 'MIRROR BOX' ILLUSION:
# MANIPULATION OF VISUAL INFORMATION DURING BIMANUAL COORDINATION IN CHILDREN WITH AND WITHOUT SPASTIC HEMIPARETIC CEREBRAL PALSY

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A thesis submitted in partial fulfilment of the requirements of the Manchester Metropolitan University for the degree of Doctor of Philosophy

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**Abstract**

The object of this thesis was to improve our understanding of bimanual coordination and neuromuscular activation in children with and without spastic hemiparetic cerebral palsy (SHCP) and to gain insight into the contribution of visual information towards interlimb coupling. The availability of visual information was manipulated by placing a glass screen, opaque screen or a mirror ('mirror box') between the arms. Using this arrangement, visual information was available from both arms (glass condition), from one arm only (opaque screen condition), or from one arm and its mirror reflection ('mirror (box)' condition) that was superimposed on the arm behind the mirror. When both arms were moved simultaneously in the latter condition, children with a strong asymmetry between body-sides as a result of SHCP saw a visual perception of a zero lag, symmetric movement between the two less impaired arms. Without visual manipulation it was found that children with SHCP exhibited a similar mean coordination pattern compared to typically developing (TD) children, but had greater movement variability between the arms. Additionally, children with SHCP had higher intensities of mean neuromuscular activity and the movement was characterised by longer phases of eccentric and concentric activity, indicating more co-activation, especially in the more impaired arm. The electromyography (EMG) signals yielded a higher mean power frequency in all muscles of the more impaired arm and the wrist and elbow flexors of the less impaired arm, which reflected a relatively higher contribution of type II muscle fibres compared to TD children. While manipulation of visual information did not affect the bimanual coordination or neuromuscular activation in TD children, movement variability in children with SHCP was significantly greater in the screen condition compared to the glass and mirror conditions. Furthermore, the EMG intensities in the shoulder muscles of children with SHCP were lower when veridical visual feedback was absent (i.e., screen and mirror conditions). Similar attenuating effects of the mirror were found for the relative durations of eccentric and concentric activity in the elbow muscles. These findings indicated that the movement difficulties in children with SHCP may be caused by a discrepancy between actual visual feedback and the internal efference copy of a movement. Removing actual visual information of the more impaired arm and replacing it with a mirror reflection of the less impaired arm seemed to improve their motor behaviour during interlimb coupling compared to the other conditions.

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# CHAPTER 1

# GENERAL INTRODUCTION

Anyone who has (re)started a sport or leisure activity following a long period of respite will know that your muscles will feel sore afterwards. Wherever you have delayed onset of muscular soreness in your back, thighs or arms, it will dominate your every movement the next morning. From putting on your socks, walking down stairs or opening a jam-jar, you never realized that you used a certain muscle (group) for so many different tasks. You suddenly no longer perceive your body as a whole, which works effortlessly to make all kinds of complex movements, but as an enormous amount of singular parts that all need to be accurately controlled and coordinated with one another. It is after such an experience that you realize that your body is the finest instrument you will ever own. From a human movement scientist point of view it is intriguing to identify and understand the strategies the body uses to coordinate these different parts, in order to perform elegant and sophisticated movements. More importantly, what strategies are used when deficits in the system occur? These strategies do not only include how the system (re)organizes the different mechanical parts, but also how information from the environment is used to control movement. For instance, what consequences do distortions to the visual, neural or muscular system have on movement? And what strategies are used to compensate for these impairments? Following on from those questions, we can ask ourselves how we can possibly manage compensatory or prevent detrimental strategies in order to increase functional capacities of individuals with special needs. The object of this thesis is to improve our understanding of bimanual coordination in children with and without spastic hemiparetic cerebral palsy (SHCP) and gain insight into the contribution of visual information towards interlimb coupling.

**Cerebral Palsy**

Cerebral palsy (CP) is a broad term that describes a group of congenital neurological brain disorders which can be acquired between conception and up to 2 years post-natal (Miller, 2005). The precise prevalence of CP is difficult to determine but it is generally accepted at 2 – 2.5 per 1000 live births (Lin, 2003). In a large number of cases the exact aetiology is unknown, but possible causes of CP might be brain hypoxia, haematoma, genetic susceptibility, or infections. Although CP is a non-progressive brain disorder, differences in an individual's movement compared to his/her typically developing (TD) peers become more apparent during development. Additionally, depending on the individual's classification of CP (i.e., type of movement impairment, number of affected limbs and severity, which will be discussed in the following sections) the disorder has an impact on their functional independence.

Spasticity comprises approximately 70% of all cases with CP. This form is caused predominantly through damage to the motor cortex and/or pyramidal tract (Miller, 2005). Affected individuals experience a large number of neurological and muscular deficiencies, which include abnormalities in the muscle stretch reflex, higher velocity-dependent resistance during motion (Miller, 2005) and limitations in proprioceptive feedback from the extremities (Van Der Weel et al., 1995). These deficiencies result in a wide range of functional difficulties including a decrease in range of motion and muscular strength and an increase in joint stiffness (cf. Steenbergen et al., 2008). Interestingly, the deficiencies caused by spasticity are more pronounced in the distal part of the limb compared to the proximal part (Wakeling et al., 2007; Wiley & Damiano, 1998). Secondly, athetoid or dyskinetic CP (20% of cases) is caused predominantly by damage to the basal ganglia. This results in a continuous change in muscle tone, which leads to slow involuntary movements in the trunk and upper and lower extremities (Miller, 2005). Finally, ataxia (10% of cases) is caused by lesions to the cerebellum and vestibular organ and causes balance and coordination problems for the individual (Miller, 2005). Although the above described classification seems unambiguous, a large variation between individuals within the same sub-class (heterogeneity) is frequently observed.

Furthermore, an individual's movement impairment does not always involve all the limbs (quadric). Indeed, impairment might only occur in an arm and a leg on one body-side (hemi) or in either the arms or the legs (di). In rare cases three limbs might be affected (tri). In individuals with asymmetry between body-sides (i.e. hemi), studies often refer to an individual's 'affected' and 'non-affected' limb. However, evidence seems to suggest that the impairments are not exclusively restricted to one side of the body (Wiley & Damiano, 1998; Van Der Weel et al., 1995; Cooper et al., 1995; Steenbergen & Meulenbroek, 2006) and the terms 'less' and 'more impaired' body-sides seem more appropriate. Physical or mental impairments in individuals with CP depend on the size and area of damage to the brain (Netelenbos, 1998). The severity of movement impairment can be graded into paralysis (i.e. no muscle function) and paresis (i.e. partial muscle function).

This thesis will focus on children with mild SHCP. The choice not only allowed a comparison between a population of children with and without SHCP, but also within the population of children with SHCP (i.e. less impaired vs. more impaired arm). To create a more homogenous group, only one type of movement impairment sub-class (i.e., spasticity) was selected for the studies.

**Effects of spasticity on skeletal muscle properties**

Movement is produced by the contraction of skeletal muscles, which, in turn is influenced by the properties of the muscle. These properties are traditionally divided into three main categories: (1) architectural properties, which are dependent on fascicle orientation (i.e., parallel or pennate), (2) the structural properties, reflected in fibre thickness, length and type, and (3) state of the muscle, defined by strength, fatigability and the nature of the activation (i.e., as a synergist or an antagonist; Rozendal & Huijing, 1998; Wilmore & Costill, 1999).

Although not always in similar detail, all three muscle properties have been investigated in children with SHCP. Recently, Mohagheghi et al. (2007) found that the pennation angle of the muscle fascicles in the gastrocnemius was similar between the body sides. However, the muscle fascicles' length and thickness in the gastrocnemius at rest were smaller in the more impaired leg compared to the less impaired leg. Additionally, the leg muscles of children with spasticity had higher mean power frequencies of their electromyography (EMG) signals during walking compared to TD children (Wakeling et al., 2007), which is indicative of a higher distribution of type II muscle fibres and/or a differential motor unit recruitment (favouring type II fibres; Kupa et al., 1995). A couple of studies have attempted to quantify muscle fibre distribution in the lower (Ito et al., 1996; Rose et al., 1994) and upper limbs (Pontén et al., 2005) of children with SHCP through muscle biopsy. The results, however, were inconclusive (for a review see Lieber et al., 2004) and they were not directly related to movement in children with SHCP, which is an important shortcoming that will be addressed in this thesis. Finally, with regard to the state of the muscle it was found that muscle strength was lower in the more impaired leg compared to the less impaired leg (Wiley & Damiano, 1998) and that co-activation was greater during knee extension in children with CP compared to TD children (Ikeda et al., 1998).

In sum, although the cause-effect relationship between muscle structure and state is unclear in children with SHCP, the findings above suggest that SHCP is accompanied with changed muscle properties that may account in part for the differences in muscle function, which in turn affects motor behaviour. Previous research on muscle properties of children with SHCP has predominantly focussed on muscles in the lower extremities (Mohagheghi et al., 2007; Wakeling et al., 2007; Perry et al., 2001; Ikeda et al., 1998; Wiley & Damiano, 1998). In contrast to the upper extremities, which are mainly used for activities requiring more accurate movements such as grasping, holding and manipulating objects, the lower extremities are typically involved in weight bearing activities such as standing and walking. Given this task-related discrepancy, it is conceivable that SHCP may affect the muscle properties of the lower and upper limbs differently. This shortfall in the current literature is an important starting point for the research in this thesis.

**Bimanual coordination in typically developing children**

Activities in daily life which involve both arms moving and working together are very common and diverse. Tasks such as washing dishes, typing and driving impose their own specific spatio-temporal constraints on the interlimb coordination (Steenbergen et al., 2003). However, fundamental research revealed that adults can perform only two bimanual coordination patterns without much learning that are reproducible and have low interlimb temporal (i.e., timing) variability (Kelso, 1995). These patterns are in-phase, where the homologous muscle groups contract simultaneously, and anti-phase, where contractions occur half a phase out of synchrony. Although TD children as young as 4-years can perform the same bimanual coordination patterns, the interlimb temporal variability is higher compared to adults (Robertson, 1999). The development of bimanual coupling in TD children has been investigated in a variety of tasks, which include clapping and continuous circle drawing in 3 – 10 year olds (Robertson, 2001; Fitzpatrick et al., 1996). The results from both studies found that the developmental progression mainly involved decreases in temporal variability of the coordination between the arms, which was particularly significant around the age of 7 years.

The research into the spatial coupling between the arms during bimanual coordination has received far less attention, especially in children (Steenbergen et al., 2003). Franz et al. (1991) investigated the effect on the movement path in adults when different shapes were drawn simultaneously. In this experiment participants were asked to draw a circle with one hand and a line with the other. The results showed that the movement path of the arm when drawing a circle became more line-like, whereas the line drawn by the contralateral had became more circle-like. This spatial magnet effect provides evidence that both spatial and temporal constraints play an important role in the coordination of bimanual coordination. Although the spatial magnet effect has not been explicitly investigated in children, the presence of mirror movements (i.e., unintended movements in one arm when the other is moved) in TD children (Kuhtz-Buschbeck et al., 2000) suggest its likely existence.

Traditionally it was thought that motor commands limit the ability to perform bimanual coordination to an 1:1 ratio between the arms, probably originating from the anatomical structure of the nervous system. However, previous studies found that a switch in visual attention from the dominant arm to the non-dominant arm also has an effect on bimanual coordination in adults (Amazeen et al., 1997; Franz, 2004) and in children (Pellegrini et al., 2004). The influence of visual information exerted on bimanual coordination is highlighted further in an experiment by Mechsner et al. (2001). Adults were able to easily perform highly complex bimanual movements (i.e., ratio of 4:3, 2:1 and 3:2 between the arms) when visual feedback was manipulated such that it represented a simple 1:1 circular ratio of the arms (see also Shea et al., 2008). Although similar research has not been conducted in children, Von Hofsten and Rösblad (1988) did investigate the dependency on visual information to perform a pointing task accurately during development. Children aged 4 – 12 years were asked to place pins underneath a table-top at positions they saw or felt on the table-top. The study showed that the older children were more accurate than the younger children and that the children, irrespective of age, performed better (i.e., more accurately) when visual information was available compared to when it was absent. These findings in children are consistent with adult performance (Gibson, 1979) and show that during a discrete aiming task the contribution of visual information was higher compared to proprioceptive feedback but remained stable during development. However, the contribution of visual information to continuous bimanual coordination across development has not been extensively investigated.

The developmental decrease in temporal variability during interlimb coordination observed by Robertson (2001) and Fitzpatrick et al. (1996) might have, alternatively, been brought about by changes in the neuromuscular activity. That means that the more stable interlimb coupling may be directly caused by a more efficient neuromuscular activation of the older children compared to the younger children. In previous research into developmental changes on neuromuscular activity it was found that the triceps surae muscle was excessively activated in younger children during plantar flexion compared to older children (Grosset et al., 2008). Additionally, Gachoud (1983; from Bourgeois & Hay, 2003) found that during an object-lifting task the measured muscle activity progressively reduced in children aged 6 – 9 years. In this thesis it remains to be determined if developmental changes in interlimb coordination during a bimanual task are associated with a reduction in the contribution of visual information towards the movement and/or the neuromuscular activation of the arm muscles.

**Bimanual coordination in children with SHCP**

In spite of their unilateral motor impairment, children with SHCP are able to perform the in-phase and anti-phase bimanual coordination patterns to some degree. In their study, Volman and colleagues (2002) investigated the interlimb coordination between the less and the more impaired arm during continuous circle drawing when instructed to perform in-phase and anti-phase patterns. They found that the in-phase coordination pattern resulted in a decrease of interlimb temporal variability and an increase in movement smoothness of the more impaired arm compared to single-handed circle drawing. In contrast, the anti-phase coordination pattern led to an increase of temporal and spatial variability in the performance of the less impaired arm. Furthermore, Utley et al. (2004) examined the influence of object size on the interlimb coupling in children with hemiparetic cerebral palsy. In their experiment they asked children with SHCP to reach and grasp a cube uni – and bimanually. Their findings illustrated the nature and extent of bimanual coupling. In some cases the more impaired arm was influenced by the less impaired arm, while in other cases the influence between the arms was reversed. Additionally, Steenbergen et al. (2008) studied the effects of lifting objects uni – and bimanually in order to examine the differences in temporal characteristics and fingertip force control in the less and more impaired hands. The results showed that for some of the force variables the more affected hand benefited when it performed the task concurrently with the less affected hand. However, the temporal aspect of the movement for the less affected hand was influenced adversely when the task was performed bimanually. Combined, these findings have been taken to suggest that during specific bilateral movements (i.e., in-phase coordination pattern during bimanual circle drawing), the movement of the more impaired limb is adaptable and that this is at least partially based on a positive transfer from the less impaired arm (Steenbergen et al., 2008; Utley et al., 2004; Volman et al., 2002).

Many individuals with SHCP use their less impaired limb more frequently to compensate for the loss in functionality on their more impaired side (Taub et al., 1998). However, although the repeated use of the less impaired limb presumably gives individuals some degree of immediate independence (Cauraugh & Summers, 2005), it might slow or even inhibit functional movement of the more impaired limb in other contexts. The previously mentioned positive transfer between the arms forms the basic principle of bilateral movement rehabilitation, which aims to facilitate the functional motor performance of the more impaired limb by symmetrically moving both limbs together and consequently exploiting the natural tendency to synchronize movement frequency, amplitude and direction of the limbs (Cauraugh & Summers, 2005). Moreover, the manipulation of visual information has, as previously mentioned, been found to influence the bimanual coordination in typically developed adults (Mechsner et al., 2001; Shea et al., 2008). Therefore, an interesting possibility might be that functional recovery of the more affected arm in children with SHCP during bimanual movement rehabilitation might be facilitated by specific manipulations of visual information. The potential of this innovative intervention by changing the visual feedback children with SHCP receive about their more impaired arm movements during bimanual coordination will be further explored in this research project.

**The 'mirror box' as a tool for visual manipulation during bimanual movement**

According to Ramachandran (2005), the paretic movement in adults with hemiparesis due to stroke is at least partially 'learned' through an atypical interaction between the internal copy of the motor commands sent by the central nervous system to the arms (i.e., efference copy) and the signals relayed back from the peripheral senses to the brain (i.e., afference; Von Holst, 1954). In individuals without movement impairment, motor commands sent from the premotor and motor cortex to perform an action are typically damped by sensory feedback. However, when the movement is impaired, a discrepancy between the sensory feedback and the centrally generated efference copy of the motor commands causes the following motor output to be amplified, which is suggested to further deteriorate motor performance. This ‘vicious circle’ may be interrupted by reconciling (visual) sensory feedback to the efference copy by manipulating the visual feedback of the more affected arm (Ramachandran, 2005).

Visual feedback can be manipulated with a 'mirror box' to create an illusory perception of a zero lag symmetric movement between the two less impaired arms (Franz & Packman, 2004; Stevens & Stoykov, 2004, 2003; Altschuler et al., 1999; Ramachandran et al., 1995). The effect is manifested by positioning a mirror between the arms perpendicular to the chest of an individual. In a study by Altschuler et al. (1999) that had adults with hemiparesis following stroke spend four weeks practicing bilateral movements in a ‘mirror box’ or control (transparent plastic) condition, there were substantial improvements in range of motion, speed, and accuracy of the paretic arm movement following ‘mirror box’ therapy compared to the control treatment. Furthermore, in a later case study by Stevens and Stoykov (2003), two adult participants with chronic hemiparesis were found to show marked and lasting (i.e., 3-months) improvements in clinical assessments of the paretic wrist functionality and movement time following ‘mirror box’ therapy. The implication, therefore, is that by replacing veridical visual feedback from the impaired body side with a mirror reflection of the non impaired limb, movement difficulties could be reduced and the use of the paretic arm relearned in adults following a stroke (Stevens & Stoykov, 2004, 2003; Altschuler et al., 1999).

The case-studies on adults with movement difficulties arisen from hemiparesis due to stroke are encouraging. However, it is notable that there have been no previous attempts to determine whether manipulations of visual feedback using the ‘mirror box’ lead to improved movement of the more impaired arm in children with SHCP. It is important to conduct this research because while these individuals also have overt asymmetries between the body-sides that affect their daily life similar to adults with hemiparesis following a stroke, they may never have effectively learned to use their more impaired arm (Charles & Gordon, 2006). Based on the abovementioned rationale, manipulation of visual information to remove the incongruity between actual visual feedback and the efference copy may have the potential to reduce the adverse effects on movement and neuromuscular activity associated with SHCP.

**Outline of the thesis**

As the literature indicates, the effect of visual information on bimanual coordination and neuromuscular activation in children with and without SHCP has not been extensively researched, despite the scientific foundations for potential clinical benefits. In order to investigate these effects, an experimental set-up similar to that of Franz and Packman (2004) will be employed, where a divide between the arms could be changed to manipulate the availability of visual information from the more impaired/non-dominant arm. Using this arrangement, visual information was available from both arms (glass condition), from the less impaired/dominant arm only (opaque screen condition), or from the less impaired/dominant arm and its mirror reflection ('mirror (box)' condition) that superimposes the more impaired/non-dominant arm behind the mirror. The research into the effects of visual information on bimanual coordination and neuromuscular activation will facilitate the understanding of how arm coordination is controlled in this special population. Additionally, the literature review has made it apparent that the effect of SHCP on muscle properties is predominantly based on evidence obtained from muscles in the lower extremities. Given the task-related discrepancy between the lower and upper limbs, the knowledge shortfall of the muscle properties in the arms should be investigated. This information is crucial to understand arm movement coordination and to develop an adequate and goal-directed therapy, which aims to improve the functional use of the more impaired arm in children with SHCP.

In **Chapter 2** bimanual coordination and neuromuscular activation in the arms of younger and older TD children is explored when visual information is manipulated during a circular drawing task. Movement analysis is conducted to assess the temporal coupling between the arms. Additionally, EMG is measured bilaterally on the flexor and extensor muscles of the wrist, elbow and shoulder to assess muscular activation.

The kinematics of bimanual coordination in children with SHCP and TD children is investigated when visual feedback is manipulated by placing a glass screen, opaque screen or a mirror between the arms of the participants in **Chapter 3**.

In **Chapter 4** the aim is to investigate the neuromuscular activity and frequency content of the EMG signals recorded from the arm muscles in children with SHCP and TD children. This provides a detailed insight into the underlying muscular properties of the arms and neuromuscular mechanisms involved to perform a symmetrical circular bimanual task. The children performed the task when visual information is available from both arms. The EMG is recorded bilaterally on the flexor and extensor muscles of the wrist, elbow and shoulder.

The aim of **Chapter 5** was to perform an analysis of EMG and to explore the effects of visual information on the neuromuscular activity in the arm muscles of children with SHCP. Eight children with SHCP and 12 TD children performed a symmetrical circular bimanual task with visual information available from both arms (glass condition), one arm (opaque screen condition) or one arm and its mirror reflection (mirror condition). The results from this study are combined with the kinematic results in **Chapter 3** to give a more profound insight into the effects of visual information on motor behaviour.

The epilogue in **Chapter 6** summarises and discusses the main results of the thesis. Additionally, suggestions are given for further research and future direction.

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# CHAPTER 2

## Seeing the wrong arm: The effects of visual information on bimanual coordination and neuromuscular activity in children across development

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In preparation

**Abstract**

The study explored the development of arm movement coordination and neuromuscular activity in children during a bimanual symmetrical drawing task. Additionally, the contribution of visual information on motor behaviour across development was examined under conditions of visual feedback created by placing a glass screen, opaque screen or a mirror ('mirror box') between the arms. The 'mirror box' creates a visual illusion, which gives rise to a visual perception of a zero lag, symmetric movement between the two arms. Younger children (aged 5 – 10 years) exhibited a similar in-phase coordination pattern as the older children (aged 12 – 18 years), but had more temporal movement variability between the arms and higher levels of neuromuscular activity, which demonstrates an association between interlimb temporal movement variability and neuromuscular activation during development. The manipulation of available visual information did not affect the motor behaviour in children from different age groups during the performance of a bimanual circle drawing task. The results are attributed to the interchangeable contribution of visual information with proprioceptive feedback, which caused the interlimb movement variability between the conditions to be maintained.

**Introduction**

Without much learning, adults can perform only two bimanual coordination patterns that are reproducible and have low interlimb variability (Kelso, 1995). These patterns are in-phase, where the homologous muscle groups of both arms contract simultaneously, and anti-phase, where contractions occur half a phase out of synchrony. Although children as young as 4-years are able to perform the same bimanual coordination patterns as adults, the interlimb variability is higher (Robertson, 1999). The development of interlimb coupling has been investigated in a variety of tasks, including clapping (Fitzpatrick et al., 1996) and continuous circle drawing (Robertson, 2001) in children aged 3 – 10 years. Both studies found that the developmental progression involved decreases in temporal variability of the coordination between the hands, which was particularly significant around the age of 7 years. The younger children (aged 3 – 6 years) were observed to have less stable relative temporal coordination during clapping and more time in less stable patterns of coordination, higher relative phase standard deviation and more transitions between coordination patterns during circle drawing. These observations were tentatively suggested to be attributed to a difference in visual attention between the younger and older children (Robertson, 2001; Fitzpatrick et al., 1996). It is conceivable that young children, who are poor at maintaining attention (Anslin & Cuiffreda, 1983), may initially focus their visual attention on the bimanual coordination, become distracted, and then intermittently return back to the movement (Robertson, 2001; Fitzpatrick et al., 1996).While Pellegrini et al. (2004) found that a switch in visual attention between the arms did influence the temporal coupling between the arms in children, no specific attempt has been made to investigate the developmental change in the contribution of vision towards bimanual circle drawing.

The increased stability of interlimb coupling with age might be directly associated with improvements in the neuromuscular synergistic activity around the joints (e.g., less co-activation, less excessive EMG intensity). In previous research into developmental changes on neuromuscular activity it was found that the triceps surae muscle was excessively activated in younger children during plantar flexion compared to older children (Grosset et al., 2008; Lambertz et al., 2003). Additionally, it was found that the co-activation of the thigh and leg muscles during treadmill walking and running significantly decreased from 7 – 8 years and to 15 – 16 years. Similarly, Gachoud (1983; from Bourgeois & Hay, 2003) found that during an object-lifting task the measured muscle activity progressively reduced in children aged 6 – 9 years. These findings suggest that the efficiency of neuromuscular activity progressively improves during development (Grosset et al., 2008; Lambertz et al., 2003; Schmitz et al., 2002; Frost et al., 1997; Gachoud, 1983), but this has not been comprehensively researched in the arm muscles, particularly during bimanual coordination.

Traditionally it was thought that motor commands limit the ability to perform bimanual coordination to an 1:1 ratio between the arms (i.e., the arms constrained to temporal coupling), probably originating from neuromuscular structures. However, more recent studies have found that perceptual factors also influence the interlimb coordination. For example, it was shown that when adults direct their attention to the preferred arm when they oscillated handheld pendulums (Amazeen et al., 1997), the temporal interlimb coordination was lower (i.e., tighter temporal coupling). Conversely, Pellegrini et al. (2004) found in children that the temporal coupling during a bimanual reciprocal tapping task became tighter when visual attention was switched from their preferred to their non-preferred arm. Although, the results between the two studies differ, they both show evidence that visual information can exert influence on bimanual coordination in adults and in children, which is highlighted further in an experiment by Mechsner et al. (2001). In this study, adults were able to easily perform highly complex bimanual movements (i.e., ratio of 4:3, 2:1 and 3:2 between the arms) when visual feedback was manipulated such that it represented a simple 1:1 circular ratio of the arms (see also Shea et al., 2008). Although similar research has not been conducted in children, Von Hofsten and Rösblad (1988) did investigate the change in dependency of visual information during a quasi-bimanual pointing task throughout development. Children aged 4 – 12 years were asked to place pins underneath a table-top at positions they saw and/or felt with the other hand on the table-top. The results showed that older children were more accurate than younger children and that the children, irrespective of age, performed better (i.e., more accurately) when visual information was available compared to when it was absent. These findings in children are consistent with adult performance (Gibson, 1979) and show that during a discrete pointing task the contribution of visual information is higher compared to proprioceptive feedback but remains stable during development (see also Elliott et al., 1991). However, the role of visual information in continuous bimanual coordination across development has not been extensively investigated.

A possible way to examine the contribution of visual feedback to arm coordination and neuromuscular activity during a bimanual movement could simply be conducted by having children perform the task with and without visual feedback of the contralateral arm. For instance, the placement of a transparent (glass) divide between the arms allows children to receive visual information of both the arms, but an opaque screen positioned between the arms occludes the view of one arm, while the other can still be seen. The inclusion of an extra condition where children receive illusory visual feedback affords the possibility to investigate the contribution of visual information even further. By placing a mirror between the arms, the mirror reflection of one arm becomes a superimposed image of the other. When both arms are moved simultaneously, a strong visual illusion is created where the arms are moving in perfect zero lag symmetry with each other (Ramachandran & Rogers-Ramachandran, 1996; Ramachandran et al., 1995). If the contribution of visual information during bimanual circle drawing alters during development, the manipulation of visual feedback (i.e., glass, opaque screen, and mirror) will affect the interlimb coordination and/or the neuromuscular activity differently.

The first aim of this study was to examine the developmental changes in movement coordination and neuromuscular activity during the performance of a symmetrical bimanual movement. Based on the current literature, it was hypothesized that older children would perform the simultaneous arm movement with lower levels of interlimb movement variability and neuromuscular activity compared to younger children (Grosset et al., 2008; Lambertz et al., 2003; Robertson, 2001; Fitzpatrick et al., 1996). The second aim was to investigate the effects of visual manipulation on the interlimb coordination and neuromuscular activity across development during a symmetrical bimanual movement. It was expected from the aforementioned Von Hofsten and Rösblad (1988) study that the manipulation of the visual feedback from the contralateral arm would affect the temporal coupling and neuromuscular activity of the children, irrespective of age.

## Methods

*Participants*

The emergence of more adult-like bimanual coordination was reported to occur after the age of 10 years (Pellegrini et al., 2004; Robertson, 2001; Lazarus & Todor, 1987). Therefore children aged ten years or younger and (adolescent) children twelve years or older were recruited for the study. Ten participants were recruited as part of the older aged group (mean age = 14.8 years, SD = 1.8 years, age-range 12-18 years, 6 males and 4 females). All the participants in this group indicated they were right-hand dominant (i.e., writing hand). Additionally, ten children were recruited as part of the younger aged group (mean age = 8.6 years, SD = 1.6 years, age-range 5-10 years, 7 males and 3 females) of who nine participants indicated they were right-hand dominant and one participant indicated to be left-hand dominant. Participants were excluded from the study if they had any neuromuscular disorders, pain in either of their upper limbs, a visual impairment which was not corrected to normal, or could not adhere to the required task. The experiment was conducted in accordance with the Declaration of Helsinki. Written informed consent was given by the participants' parents and written informed assent was obtained from all participants. The institutional research ethics committee approved all procedures.

*Materials and procedure*

A divide (width 0.06 m, depth 0.75 m, height 0.39 m) was securely placed between two custom-built wooden boxes (width 0.59 m, depth 0.17 m, height 0.39 m). The divide was a transparent screen (glass condition), an opaque screen (screen condition) or a mirror (mirror condition). In this way, visual information could be manipulated and was available from both arms (glass condition), from one arm only (opaque screen condition) and from one arm and a mirror reflection ('mirror (box)' condition), which superimposed the arm behind the mirror, resulting in an illusory visual perception of a zero lag, symmetric movement between the two arms. The participant placed one arm on either side of the divide and angled their head towards the side of their dominant arm (Fig. 2.1). In each hand participants gripped a handle from an arm ergometer (871E, Monark Exercise AB, Vansbro, Sweden). Each handle was attached to the edge of a wooden disc with a radius of 0.10 m, which spun freely through 360$^{o}$ around a vertical axis. The axes were fixed to a wooden plateau (width 0.60 m, depth 0.46 m, height 0.04 m) and were located 0.31 m apart. Participants sat on a height-adjustable stool at a table with the elbow flexed to 90° and both feet flat on the floor with the knees also bent to 90°.

Glass Screen Mirror

**Figure 2.1:** Experimental set up of the 'mirror box' during the glass (left panel), screen (middle panel) and mirror (right panel) conditions. The participant viewed the bimanual task from their dominant hand side. The rotating discs are not shown in this image.

The start positions for the arms were at the inner most part of each of the circle (i.e. nine o'clock for the right arm and three o'clock for the left arm). Participants were asked to perform an inward symmetrical circular bimanual task (i.e. the right arm rotated anti-clockwise and the left arm rotated clockwise irrespective of hand dominance). The discs were rotated continuously at a self-selected pace after the start instruction was given and until they were instructed to stop. The participants were also instructed to keep movement time (i.e., movement frequency) constant during the experimental trials. The inward symmetrical circular task the participants were asked to perform afforded the possibility to concurrently measure the EMG intensities of the active homologous muscle groups on each body-side.

Light emitting diodes were bilaterally attached to the skin with double-sided tape over the dorsal tuberculum of the radius (wrist). Two serially-connected units each containing three infrared cameras (3020 Optotrak, Northern Digital Inc., Waterloo, Canada) were used to measure the 3D position of the wrists at a sample rate of 200 Hz. Pilot studies showed that participants were able to maintain an anatomical neutral position of the wrist during the movement, which ensured reliable recordings. Additionally, from eight older and ten younger children superficial EMG was bilaterally recorded from the main muscles around the wrist, elbow and shoulder: flexor digitorum superficialis (FDS), extensor carpi radialis brevis (ECRB), biceps brachii brevis (BBB), tricpes brachii longus (TBL), deltoideus pars anterior (DPA) and deltoideus pars posterior (DPP). A ground electrode was placed over the acromion on the side of the dominant hand. Pairs of disposable Ag/AgCl surface EMG electrodes (Blue Sensor Electrodes N, Ambu Inc., Glen Burnie, MD, USA) with a gel-skin contact, active detection area of 15 $mm^2$ for each electrode and a 20 mm centre to centre inter-electrode distance, were placed in parallel with the muscle fibre direction over the muscle bellies after cleaning and gentle abrasion of the skin. The EMG signals were amplified 20 times, high-pass pre-filtered at 10 Hz and AD-converted at 1000 Hz with a 22-bit resolution (Porti-17, Twente Medical Systems, Enschede, The Netherlands, input resistance $>10^{12}\Omega$, CMRR > 90 dB) and stored on a computer. The EMG signals were band-pass filtered with a zero lag 2nd order Butterworth filter between 10 and 400 Hz and then full-wave rectified. The static maximum voluntary contraction of the arm muscles was measured in four positions of the rotation discs (i.e. at the starting point, +90°, +180° and +270°). Participants performed two repetitions in each position and with each arm consecutively. The highest value of each muscle from the eight attempts in each arm was recorded as the maximum voluntary contraction. The EMG and motion capture computers were synchronised with a pulse signal.

In experimental trials, participants performed the bimanual coordination task in three conditions that differed according to the divide placed between the arms. Three trials per condition were recorded and the condition order was pseudo-randomised across participants. To keep the point of gaze constant between trials, a reference dot was placed between the start position and the divide. Participants were asked to keep the reference point in their central viewing area while performing each trial in order to prevent them focusing on one arm only during the screen condition. To recover from any fatigue or drop in concentration that might have occurred during the experiment, participants were given short breaks between trials. In order to keep the participants motivated, they were told that rotating the handles symmetrically resulted in more points being scored, and that at the end of the experiment they could trade the points for a small gift.

*Data analysis*

2D kinematic data from the wrist were analyzed from the first 2 cycles completed by the participant in each trial. Trials were excluded from analysis if participants performed an outward coordination mode or a transition from a symmetric to an asymmetric coordination pattern occurred. In total, 9 out of 180 trials were excluded from analysis. The duration of the 2 cycles was determined to enable calculation of movement time.

Interlimb coupling was assessed based on both position and velocity of the two limbs (Kelso, 1995). The phase portrait obtained when the position of each limb was plotted against its velocity allowed the calculation of the continuous relative phase (CRP) of each limb separately, according to the following formulas:

$$\varphi_{D} = \arctan\,[(dS_{D} \cdot dt^{-1}) \,/\, S_{D}]$$

and

$$\varphi_{ND} = \arctan\,[(dS_{ND} \cdot dt^{-1}) \,/\, S_{ND}],$$

where $\varphi_{D}$ and $\varphi_{ND}$ are the phase of the dominant and non-dominant arm respectively, and $S_{D}$ and $S_{ND}$ are the position time series and $dS_{D} \cdot dt^{-1}$ and $dS_{ND} \cdot dt^{-1}$ represent instantaneous velocity. Before the calculation of $\varphi_{ND}$, the sign of the position time series of the non-dominant arm was inversed to an anti-clockwise trajectory. The CRP indicated the degree of coupling (i.e. synchronicity) between the arms and denoted by $\Phi$, was calculated as:

$$\Phi = \varphi_{D} - \varphi_{ND},$$

where a positive value for $\Phi$ implied a dominant arm lead and a negative value a non-dominant arm lead. Moreover, $\Phi = 0^{o}$ indicates perfect symmetrical and $\Phi = 180^{o}$ indicates perfect asymmetrical coordination, which means that the limbs were behaving in exactly the same or opposite way, respectively. The mean and standard deviation (SD) of the CRP during the two cycles were calculated for each trial to assess the temporal relation and its variability between the arms.

Bilateral EMG recordings from the 12 muscles were analyzed from the first 2 cycles completed by the participant. Trials were excluded on the same basis as for kinematic data (i.e., incorrect execution of the required movement). In order to remove the high frequency signal component from the EMG data, the signals were smoothed with a low-pass 2nd order Butterworth filter at a cut-off frequency of 6 Hz.

The signals were normalized to the highest muscle activity obtained from the static maximum voluntary contraction measurements and the average EMG amplitude (neuromuscular activity) was calculated.

*Statistical analyses*

The values for mean CRP could in theory range from $+180^{o}$ to $-180^{o}$, both of which represent perfect asymmetrical coordination mode. Usually circular statistics need to be used to obtain a measure of dispersion with this type of variable. However, in the current study, participants were asked to keep the arms as symmetrical as possible in an in-phase coordination mode. Therefore, in practice, the values were in the range of $+90^{o}$ and $-90^{o}$, which implied that normal distribution statistics could be used. A mixed ANOVA with one repeated factor, divide (3 levels) and one independent factor, group (2 levels), was used to compare the older with the younger children on mean CRP and SD CRP. Additionally, for mean EMG amplitude a mixed ANOVA with two repeated factors, arm (2 levels) and divide (3 levels) and one independent factor, group (2 levels) was used to compare the younger with older age group. In cases where the sphericity assumption was violated, Greenhouse-Geisser adjustments were made. Fishers' LSD was used for post hoc analysis, the alpha-level was set at 0.05, and standard error was reported to indicate the true mean variability.

**Results**

There was no significant difference between the groups for movement time (older: 3.15 ± 0.56 s; younger: 3.58 ± 0.56 s) or mean CRP (older: $-6.5 \pm 2.4\,^{o}$; younger: $-3.0 \pm 2.4\,^{o}$; $F = 1.0$; $p = 0.32$). This indicates that the two groups performed the task at a similar movement frequency and that the younger children were able to maintain a similar coordination pattern (mean CRP) as the older children. Furthermore, the results indicate that both groups tended to lead with the non-dominant arm. However, as seen in Fig. 2.2, children in the younger group exhibited significantly higher SD CRP ($F(1,18) = 10.38$, $p < 0.01$) compared to the older children. Additionally, children in the younger age group had significantly higher levels of mean EMG activity for ECRB, BBB, DPA and DPP (all: $F(1,16) > 4.14$, $p < 0.05$; see Fig. 2.3).

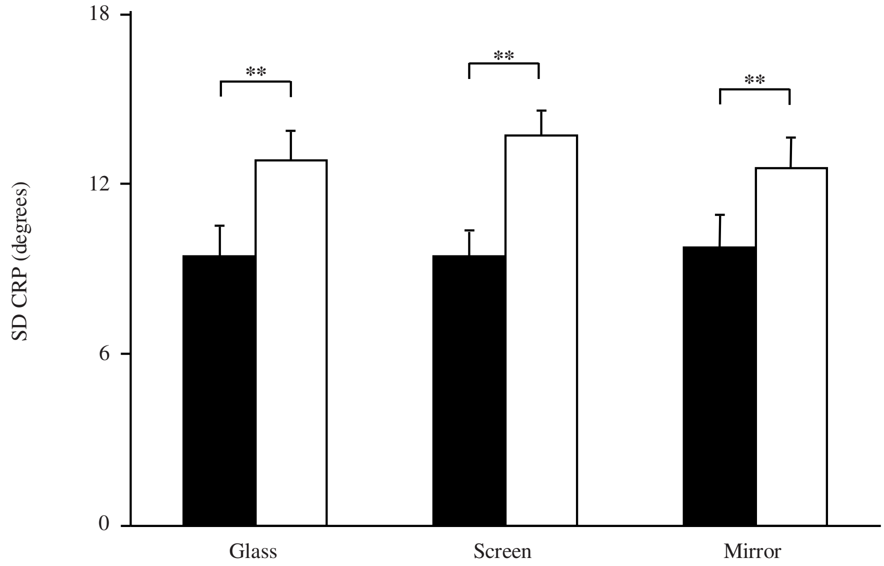


**Figure 2.2:** Standard deviation of the continuous relative phase for the older (solid) and younger group (open) during the glass, screen and mirror condition of the mirror box. **$p < 0.01$. Error bars (SE) indicate true mean variability.

There were no significant differences between the divides for the movement time (glass = 3.17 ± 0.37 s; screen = 3.56 ± 0.51 s; mirror = 3.37 ± 0.37 s), mean CRP (glass = -5.8 ± 2.1$^{o}$; screen = -5.7 ± 2.1$^{o}$; mirror = -2.7 ± 1.8$^{o}$), SD CRP (glass = 11.2 ± 0.7$^{o}$; screen = 11.6 ± 0.6$^{o}$; mirror = 11.2 ± 0.8$^{o}$; all: $p > 0.18$) or for the mean EMG in the measured arm muscles (all: $p > 0.06$). However, a significant group by divide interaction was found for mean EMG in the FDS ($F(2,32) = 4.25$, $p < 0.05$). Post hoc tests were unable to locate the source of the interaction (all: $p > 0.12$). However, inspection of the data suggests a subtle difference between the older and the younger group in the mirror condition (4.3 and 9.1 %MVC, respectively) compared to the glass (5.6 and 7.0 %MVC, respectively) and screen conditions (7.1 and 7.0 %MVC, respectively). This was confirmed by an independent t-test between the age groups in the mirror condition ($t(16) = -2.22$, $p < 0.05$). Finally, a significant main effect of arm was found for mean EMG in BBB ($F(1,16) = 8.38$, $p = 0.01$), whereby the mean EMG activity was lower in the dominant arm (4.3 %MVC) compared to the non-dominant arm (6.3 %MVC). There was no other significant interaction for mean EMG in the other muscles (all: $p > 0.07$), for the movement time ($p = 0.31$) or for the other movement coordination variables (both: $p > 0.64$).

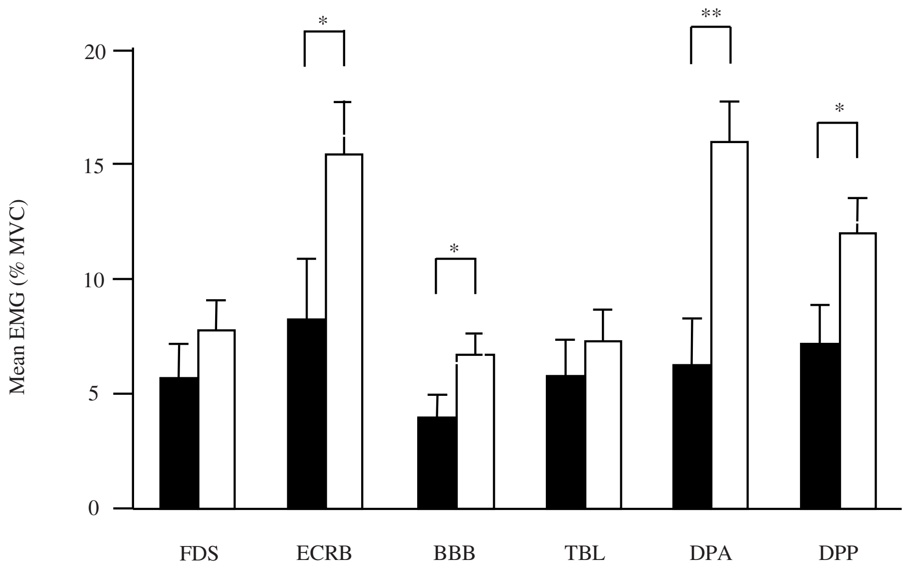


**Figure 2.3:** Mean EMG activity of the flexor digitorum superficialis (FDS), extensor carpi radialis brevis (ECRB), biceps brachii brevis (BBB), triceps brachii longus (TBL), deltoideus pars anterior (DPA) and deltoideus pars posterior (DPP) muscles for the older group (solid) and younger group (open) during execution of the bimanual task. *$p < 0.05$ and ** $p < 0.01$. Error bars (SE) indicate true mean variability.

**Discussion**

The aim of this experiment was to examine the developmental changes in the coordination of and the visual contribution to a bimanual symmetrical drawing task. The current study found that the younger children were able to maintain a similar in-phase coordination pattern (i.e., mean CRP and movement time) similar to the older age group. However, younger children had greater interlimb movement variability (SD CRP) and higher levels of neuromuscular activity compared to the older children. Furthermore, it was found that the in-phase coordination pattern, temporal movement variability and mean neuromuscular activity were unaffected in the glass, screen and mirror condition. The exception to this was the mean neuromuscular activity for the FDS muscle were there seemed to be a small difference between the groups during the mirror condition that was not observed in the other conditions. These results suggest that the decrease in movement variability with development when performing a symmetrical bimanual circular task is associated with changes in the neuromuscular activity rather than with changes in the contribution of visual information towards interlimb movement.

The reduction in interlimb movement variability and neuromuscular activity with age are in agreement with previous research (Grosset et al., 2008; Bourgeois & Hay, 2003; Robertson, 2001; Fitzpatrick et al., 1996; Gachoud, 1983) and demonstrates an association between these factors during the development of bimanual coordination. The decrease in interlimb movement variability shows that more stable patterns of coordination (i.e., tighter temporal coupling) between the arms are established in children aged 12 years and older (Robertson, 2001; Fitzpatrick et al., 1996). In addition, the reduced EMG intensity in the older children implies a more efficient activation of the involved muscles during the task (i.e., less neuromuscular activation for the same task) compared to the younger children (Grosset et al., 2008). Although it is not possible to establish a direct cause and effect relationship between the interlimb movement variability and neuromuscular activity, the results show that developmental changes occur at different levels of motor system and emphasize the need to investigate each of them in future research.

Unexpectedly, the manipulation of visual information did not affect the bimanual movement coordination or the mean neuromuscular activation of the children as was predicted based on the findings of Von Hofsten and Rösblad (1988). They found that when visual information was available, both younger and older children were more accurate at pointing compared to when visual information was absent. The divergence with the current results might have been caused by the different types of tasks (i.e., discrete aiming vs. continuous circle drawing). The bimanual pointing task of Von Hofsten & Rösblad (1998) required the accurate spatial matching of both hands, whereas continuous circle drawing required exact timing between the hands. Interestingly, changes to the spatial aspect of bimanual coordination were found in adults when visual information was manipulated (Franz & Packman, 2004). In a similar experimental set-up to the current study[1], they found that the sizes of the circles were similar when drawn by the left and right hand simultaneously during the glass and mirror condition. However, in the opaque screen condition the spatial coupling between the arms was reduced (i.e., size of the circles between left and right hand were significantly different). Furthermore, they found that

[1] With the exception that the adults could draw the circles without the circle diameter constrained.

the visual manipulation did not affect the temporal coupling. In the current experiment, the constrained circle diameter reduced the spatial component of the task, but the temporal aspect of the task was still present. Based on the available evidence, it seems that the visual feedback might predominantly contribute towards the spatial coupling between hands, whereas proprioceptive information may be more involved in monitoring the temporal component of bimanual coordination. Future research should examine the effects of distorted proprioceptive information on the temporal aspects of a continuous bimanual circle drawing task in both adults and children.

This study tried to distinguish if a decrease in the interlimb movement variability with development was associated with changes in the contribution of visual information or the neuromuscular activation. The results are evidence that during development a decrease in the temporal interlimb movement variability can be observed without an obvious change in the contribution of visual information. Perhaps the children in the younger age group of the current study may have been too old (8.6 years on average, range: 5-10) to be able to detect a difference in visual dependency, but overall the current findings indicate that visual factors were of less importance for the increased movement stability than the neuromuscular factors. While the increased movement stability may be associated with a reduction in neuromuscular activation, other factors may also contribute to the current findings. Firstly, it has been reported that mental concentration and visual attention are more likely to drift in younger children (Anslin & Cuiffreda, 1983). Although, the protocol was designed to minimise the effects of these factors, (i.e., short trials, frequent prompting of the task and regular breaks), the mental concentration and visual attention of the children were not directly measured during the experiment and, therefore, differences of these factors between the younger and older group can not be ruled out. An intermittent focus of concentration and attention may have contributed to an increase in interlimb movement variability in the younger age group. Future work needs to directly investigate the effects of these fluctuations of concentration and attention on bimanual coordination. Secondly, a difference in mean neuromuscular activity between the two age groups might also have been caused by variations in anatomical characteristics (i.e., length of the arms) between the participants relative to the size of the rotating discs. The diameter of the rotating discs was fixed (20 cm.) and therefore could not be scaled to the length of the participant's arm. This might have caused the neuromuscular activity to be higher in the younger children. However, the diameter of the discs was chosen based on data from previous research where children aged 4 – 7 years drew circles that were not constrained to a particular shape or size (Robertson, 2001; Lantero & Ringenbach, 2007). The children tended to draw the circles with a diameter of approximately 20 cm without instruction to do so. Moreover, prior to data collection it was ensured that the participant could comfortably rotate the discs and did not need to reach excessively when performing the task. However, to clarify this point it would be useful in the future to measure kinematics and neuromuscular activity when children perform a bimanual drawing task with varying circle diameters or when the size of the rotating discs are scaled to the anatomical characteristics of the child.

Previous research with adults demonstrated that the dominant arm was the leading limb in bimanual tasks (Franz, 2004; Franz et al., 2002; Amazeen et al., 1997; Swinnen et al., 1996). It therefore seems surprising that in the current study the participants tended to lead the bimanual movement with their non – dominant arm (i.e. the mean CRP was generally negative). A possible explanation for this discrepancy might reside in the altered constraints imposed on the arm movement (i.e., range of motion in the shoulder and elbow joints). In order for the children to perceive the visual illusion in the mirror, they needed to adopt a specific head, neck and trunk position (i.e., angled towards the dominant arm). In pilot data, it was found that when participants angled their head towards the side of their non-dominant arm, a switch in arm lead occurred (i.e., the arm on the contralateral side of the divide lead the movement), although more research is needed to confirm this observation.

In sum, this study showed that the manipulation of available visual information did not affect the motor behaviour in children from different age groups during the performance of a bimanual circle drawing task. This suggests that the contribution of visual information towards bimanual movement might have been interchangeable with proprioceptive feedback to maintain interlimb movement variability between the conditions. Furthermore, younger children exhibited more temporal movement variability between the limbs and higher levels of neuromuscular activity compared to older children during a symmetrical bimanual movement. While a direct relationship between the two factors can not be established in this study, the findings demonstrate an association between interlimb temporal movement variability and neuromuscular activation during development. However, further research is required to investigate the effects of mental concentration, visual attention and anatomical characteristics on motor behaviour, which can not be disregarded during development.

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# CHAPTER 3

## The 'mirror box' illusion:
## Effect of visual information on bimanual coordination in children with spastic hemiparetic cerebral palsy

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**Abstract**

The study examined symmetrical bimanual coordination of children with spastic hemiparetic cerebral palsy (SHCP) and a typically developing (TD) control group under conditions of visual feedback created by placing a glass screen, opaque screen or a mirror ('mirror box') between the arms. The 'mirror box' creates a visual illusion, which gives rise to a visual perception of a zero lag, symmetric movement between the two arms. Children with SHCP exhibited a similar mean coordination pattern as the TD control group, but had greater movement variability between the arms. Furthermore, movement variability in children with SHCP was significantly greater in the screen condition compared to the glass and mirror condition, which were similar to each other. The effects of the availability of visual feedback in individuals with hemiparesis are discussed with reference to central and peripheral mechanisms.

**Introduction**

Cerebral palsy (CP) is a broad term that describes a group of congenital neurological brain disorders. A common form of CP is spastic hemiparetic cerebral palsy (SHCP), which is caused predominantly through unilateral damage to the motor cortex and/or pyramidal tract. Affected individuals have an increased muscle tone in certain antagonist muscle groups on the side of the body contralateral to the lesion. This leads to abnormalities in the muscle stretch reflex and higher velocity-dependent resistance during motion (Miller, 2005). In combination, these effects influence the motor behaviour of individuals with SHCP such that they exhibit irregular or jerky movements of the contralateral limbs. Furthermore, while a unilateral cerebral lesion has greatest impact on the contralateral side, it has been reported that movement of limbs on the side ipsilateral to the lesion is also mildly impaired (Van Der Weel et al., 1995). Still, it is notable that there is a strong asymmetry between body sides in individuals with SHCP, and hence the less impaired limb is often used as a 'control' against which the more impaired limb can be compared (Steenbergen et al., 2008).

Many individuals with SHCP use their less impaired limb more frequently to compensate for the loss in functionality on their more impaired side (Taub et al., 1998). However, although use of the less impaired limb presumably gives individuals some degree of immediate independence (Cauraugh & Summers, 2005), this might slow or even inhibit functional use of the more impaired limb in other contexts. Based on this reasoning, there have been two main approaches to therapy, which specifically aim to improve functional use of the more impaired upper limb. The first approach, known as the constraint-induced therapy, restrains movements of the less impaired limb by placing it in a sling, forcing individuals to use their more impaired limb (Taub et al., 1998). Restraint of the less impaired arm appears to be effective in overcoming learned non-use in daily life activities (Taub et al., 1998). The second approach, known as bilateral movement rehabilitation, aims to facilitate functional use of the more impaired limb by symmetrically moving both limbs together and exploiting the natural tendency to synchronize movement frequency, amplitude and direction (Cauraugh & Summers, 2005). This has been particularly effective at improving coupling between the arms of children with hemiparetic CP when performing symmetrical bimanual movements (Steenbergen et al., 2008; Volman et al., 2002; Utley & Sugden, 1998; Sugden & Utley, 1995). For instance, when children with SHCP draw symmetrical circles with both hands, there is a decrease of temporal variability and an increase of smoothness of circle drawing (Volman et al., 2002). These findings have been taken to suggest that movement of the more impaired limb is adaptable and that this is at least partially based on a positive transfer from the less impaired arm (Steenbergen et al., 2008; Utley et al., 2004).

While it was traditionally thought that muscular constraints limit the ability to perform bimanual coordination, it has been shown that manipulation of visual information can also exert an influence (Mechsner et al., 2001; Shea et al., 2008). For example, it has been found that typically developed adults were able to easily perform highly complex bimanual movements (i.e., ratio of 4:3, 2:1 and 3:2 between the arms) when visual feedback was manipulated such that it represented a simple 1:1 circular ratio of the arms (Mechsner et al., 2001). An interesting possibility, therefore, might be that manipulation of visual information can also influence the movement of an individual with hemiparesis. For example, when looking at a mirror placed between the arms, the reflection of the non-paretic arm becomes a superimposition on the paretic arm, resulting in an illusory visual perception of a zero lag, symmetric movement between the two non-paretic limbs (Stevens & Stoykov, 2004, 2003; Franz & Packman, 2004). Some preliminary evidence for this position was shown in a study by Altschuler et al., (1999) that had adults with hemiparesis following a stroke spend four weeks practicing bilateral movement in a 'mirror box' or control (transparent plastic) condition. It was reported that there were substantial improvements in range of motion, speed, and accuracy of the paretic arm movement following 'mirror box' therapy compared to the control treatment. Furthermore, in a later case study by Stevens and Stoykov (2003), two adult participants with chronic hemiparesis were found to show marked and lasting (i.e., 3-months) improvements in clinical assessments of the paretic wrist functionality and movement time following 'mirror box' therapy. The implication, therefore, is that with the manipulation of visual feedback, movement difficulties could be overcome and the use of the paretic arm relearned in adults following a stroke (Altschuler et al., 1999; Stevens & Stoykov, 2004, 2003).

While case-studies on adults with movement difficulties arisen from hemiparesis due to stroke are encouraging, it is notable that there have been no previous attempts to determine whether manipulations of visual feedback using the 'mirror box' lead to improved movement of the more impaired arm in children with SHCP. This is important because while these individuals also have overt asymmetries between the body-sides that affect their daily life, they may never have effectively learned to use their more impaired arm (Charles & Gordon, 2006). To this end, the current study employed an experimental setup similar to that used by Franz and Packman (2004), where a divide between the arms could be changed to manipulate the availability of visual information from the less impaired and more impaired upper limbs. Using this arrangement, visual information can be seen from both arms (glass condition), from one arm only (opaque screen condition), or from one arm and a mirror reflection ('mirror box' condition) that superimposes the arm behind the mirror.

The first aim of this study was to examine the coordination of the upper limbs when children with SHCP, and a TD age-matched control group, performed a symmetrical bimanual movement. Based on previous research, it was expected that both groups would be able to exhibit a symmetrical coordination pattern (Volman et al., 2002; Robertson, 2001; Utley & Sugden, 1998; Steenbergen et al., 1996; Sugden & Utley, 1995). However, the children with SHCP were expected to perform the movement with more variability between the arms than the TD control population (Volman et al., 2002; Steenbergen et al., 1996).

Having determined the underlying coordination of the upper limbs in these two groups, the second aim was to examine the effects of specific manipulations of visual feedback using the 'mirror box'. It was expected that the absence of visual feedback of the more impaired arm in the screen condition would have a detrimental effect on coordination in children with SHCP because they could only rely on distorted proprioceptive feedback (Van Der Weel et al., 1995). Furthermore, based on previous observations made in adults with hemiparesis (Altschuler et al., 1999; Stevens & Stoykov, 2004, 2003), it was predicted that the illusory visual perception of a zero lag, symmetric movement between two limbs in the mirror condition would have a beneficial effect on coordination. Finally, given that in typically developed adults no effect of visual manipulation was found on temporal measures of bimanual coordination (Franz & Packman, 2004), and further that there is no reason to believe that TD children in the current study would exhibit movement asymmetries, it was anticipated that this group would perform equally well in the three conditions.

## Methods

*Participants*

The participants with SHCP were 8 children (mean age 13.9 years, SD = 2.9 years, age range = 9 – 18 years, 6 males and 2 females), who had no history of another neuromuscular disorder. Except for one, all participants indicated that their left arm was less affected than the right arm. The age-matched controls consisted of 14 TD children (mean age 13.8 years, SD = 3.0 years, age range = 9 – 18 years, 9 males and 5 females), all of whom indicated that they were right arm dominant and had no history of a neuromuscular disorder. The individual characteristics of the SHCP and TD children are presented in Table 3.1. Participants were excluded from the study if they had any pain in either of their upper limbs, an uncorrected visual impairment or could not adhere to the required task. The experiment was conducted in accordance with the Declaration of Helsinki. Written informed consent was given by the participants' parents and written informed assent was obtained from all participants. The institutional research ethics committee approved all procedures.

*Materials and procedure*

A divide (width 0.06 m, depth 0.75 m, height 0.39 m) was securely placed between two custom-built wooden boxes (width 0.59 m, depth 0.17 m, height 0.39 m). The divide was a transparent screen (glass condition), an opaque screen (screen condition) or a mirror (mirror condition). The participant sat on a height-adjustable stool and placed one arm on either side of the divide and angled their head towards the side of their dominant/less impaired arm (Fig. 3.1). In this position, each participant sat with both feet flat on the floor, knees flexed to 90° and elbows flexed to 90°. Participants then gripped in each hand a handle from an arm ergometer (871E, Monark Exercise AB, Vansbro, Sweden) that was attached to the edge of a wooden disc with a radius of 0.10 m, such that it spun freely through $360^{o}$ around a vertical axis. The axes were fixed to a wooden table top (width 0.60 m, depth 0.46 m, height 0.04 m) and were located 0.31 m apart. If a participant was unable to grip the handle because of physical impairment, the hand was placed on top of the handle by the experimenter. Two serially-connected motion analysis units each containing three infrared cameras (3020 Optotrak, Northern Digital Inc., Waterloo, Canada) were used to measure the 3D position of the wrists at a sample rate of 200 Hz. Light emitting diodes were bilaterally attached to the skin with double-sided tape over the dorsal tuberculum of the radius (wrist). Pilot studies showed that participants were able to maintain an anatomical neutral position of the wrist during the movement, which ensured reliable recordings.

**Table 3.1:** Information on the children with SHCP and their age-matched control(s).

| Participant | Age (Years) | Gender | More Impaired Arm | Severity AS / GMFCS / WeeFIM | Aetiology | Matched Control Participant (Age / Gender / Arm Dominance) | |
|---|---|---|---|---|---|---|---|
| 1 | 16.3 | F | Left | 1 / 1 / 79 | $O_2$ shortage during birth | 16.8 / F / R | - |
| 2 | 17.1 | M | Right | 2 / 1 / 91 | Cerebral haemorrhage | 17.6 / F / R | 16.2 / M / R |
| 3 | 9.3 | F | Right | +1 / 1 / 89 | Cerebral haemorrhage | 9.6 / M / R | 9.3 / M / R |
| 4 | 11.0 | M | Right | 1 / 2 / 55 | Meningitis just after birth | 10.0 / F / R | 10.6 / M / R |
| 5 | 12.8 | M | Right | 1 / 1 / 90 | Unknown | 12.4 / F / R | 12.8 / M / R |
| 6 | 13.2 | M | Right | 1 / 1 / 91 | Unknown | 14.0 / F / R | - |
| 7 | 17.4 | M | Right | 1 / 1 / 90 | $O_2$ shortage during birth | 16.7 / M / R | 17.2 / M / R |
| 8 | 14.3 | M | Right | +1 / 1 / 91 | Cerebral haemorrhage during birth & Meningitis just after birth | 14.8 / M / R | 14.6 / M / R |

*Note*. Severity of the child's impairment was assessed by a single experimenter using the modified Ashworth scale (AS) for the elbow (range: 0 – 5, higher scores denoting more spasticity), gross motor function classification system (GMFCS; range 1 – 4, higher scores denoting less gross motor functionality) and functional independence measure for children (WeeFIM; motor items only, range: 13 – 91, higher scores denoting more functional independence of the child).


**Fig. 3.1:** Experimental set up of the 'mirror box' during the glass (left panel), screen (middle panel) and mirror (right panel) condition when the participant's head is positioned towards their dominant arm side to view the bimanual task.

Before commencing the task, the arms were placed at a start position where they were at the inner most part of each of circle (i.e., nine o'clock for the right arm and three o'clock for the left arm). The participants were then asked to perform an inward, symmetrical circular movement of both upper limbs (i.e., the right arm rotated anti-clockwise and the left arm rotated clockwise irrespective of hand dominance), and maintain this coordination mode throughout the experiment. Additionally, participants were instructed to rotate the discs continuously at a self-selected pace after the start instruction was given and until they were instructed to stop. They were also requested to keep their self-selected pace (i.e., movement frequency) constant during the experimental trials, which each lasted approximately 15 seconds. Prior to data collection, practice trials were conducted to familiarize the participant with the protocol and test setup.

In experimental trials, participants performed the bimanual coordination task in three conditions that differed according to the divide placed between the arms. Three trials per condition were recorded and the condition order was pseudo-randomised across participants. To keep the point of gaze constant between trials, a reference dot was placed between the start position and the divide. Participants were asked to keep the reference point in their central viewing area while performing each trial in order to prevent them focusing on one arm only during the screen condition. To recover from any fatigue or drop in concentration that might have occurred during the experiment, participants were given short breaks between trials. In order to keep the participants motivated, they were told that rotating the handles symmetrically would result in more points being scored, and that at the end of the experiment they could trade the points for a small gift.

*Data analysis*

2D kinematic data from the wrist were analyzed from the first 2 cycles completed by the participant in each trial. The first two cycles of each trial were analyzed because some children with SHCP could only produce 2 cycles before they adopted a coordination mode that was different to the one they were instructed to produce (e.g., outward rotation of the handles or a transition from a symmetric to an asymmetric coordination). These changes away from the required coordination would have disproportionately influenced the variability of the relative phase (Volman et al., 2002), and hence they could not be included in the analysis. Moreover, for some of the children with SHCP, movement time only allowed them to complete 2 cycles within the allocated time of each trial, or the hand slipped off the handle at which point the trial was terminated. Overall, in the TD group of children, 5 out of 126 trials were excluded from analysis, whereas in the children with SHCP, 13 out of 72 trials were excluded.

The duration of the 2 cycles was determined to enable calculation of movement time. Interlimb coupling was assessed based on both position and velocity of the two limbs (Kelso, 1995). The phase portrait obtained when the position of each limb was plotted against its velocity allowed calculation of the continuous relative phase (CRP) of each limb separately, according to the following formulas:

$$\varphi_{\mathrm{D}} = \arctan\left[(\mathrm{d}S_{\mathrm{D}} \cdot \mathrm{d}t^{-1}) / S_{\mathrm{D}}\right]$$

and

$$\varphi_{\mathrm{ND}} = \arctan\left[(\mathrm{d}S_{\mathrm{ND}} \cdot \mathrm{d}t^{-1}) / S_{\mathrm{ND}}\right],$$

where $\varphi_{\mathrm{D}}$ and $\varphi_{\mathrm{ND}}$ are the phase of the dominant and non-dominant arm respectively, and $S_{\mathrm{D}}$ and $S_{\mathrm{ND}}$ are the position time series and $\mathrm{d}S_{\mathrm{D}} \cdot \mathrm{d}t^{-1}$ and $\mathrm{d}S_{\mathrm{ND}} \cdot \mathrm{d}t^{-1}$ represent instantaneous velocity. Before the calculation of $\varphi_{\mathrm{ND}}$, the sign of the position time series of the non-dominant arm was inversed to an anti-clockwise trajectory. The CRP indicated the degree of coupling (i.e., synchronicity) between the arms and denoted by $\Phi$, was derived from:

$$\Phi = \varphi_{D} - \varphi_{ND},$$

where a positive value for $\Phi$ implied a dominant arm lead and a negative value a non-dominant arm lead. Moreover, $\Phi = 0^o$ indicates perfect symmetrical and $\Phi = 180^o$ indicates perfect asymmetrical coordination, which means that the limbs were behaving in exactly the same or opposite way, respectively. The mean and standard deviation (SD) of the CRP during the two cycles were calculated for each trial to assess the temporal relation and its variability between the arms.

Additionally, it was deemed important to determine if changes in bimanual coordination as a result of manipulating visual feedback reside in the more impaired arm alone or in both the more and less impaired arm. A reduction in symmetric coordination caused by improperly timed initiation and disproportionate activation of independent muscle system, for example as a result of spasticity, is likely to result in multiple acceleration peaks. This can be measured as an increase in jerk compared to when coordination is regular and smooth (Teulings et al., 1997; Flash & Hogan, 1985). Mean jerk over the 2 cycles (unit: position/time$^3$) was calculated in both medial/lateral direction (x – axis) and posterior/anterior (y – axis) direction by taking the third derivative of the x – and y – position. Before jerk was calculated, position time signals of each trial were filtered with a bi-directional 2$^{nd}$ order Butterworth filter. The cut-off frequency was determined by taking 1 Hz lower than the frequency ascertained with the residual analysis. A lower cut-off frequency was taken to obtain a 'smoother' higher derivative of position data (Giakas & Baltzopoulos, 1997). The range of the cut-off frequency was 2 – 10 Hz.

The level of jerk depends on the size and the duration of the movements (Teulings et al., 1997), which in the present study could have differed between participants because of their different anatomical proportions and preferred movement time. Therefore, to compare intralimb stability between participants, jerk was normalized for different size and duration of movements in each trial (i.e., 2 cycles). This was done by multiplying the integrated square jerk by time$^5$/position$^2$ and subsequently the square root was taken so that normalized jerk was proportional with absolute jerk. Normalized jerk is a unit less measure and described with:

$$\textit{Normalized jerk} = \sqrt{(\tfrac{1}{2} \int dtj^2(t) \bullet time^5 / position^2)}$$

*Statistical analyses*

The values for mean CRP could in theory range from +180$^{o}$ to -180$^{o}$, both of which represent perfect asymmetrical coordination mode. Usually circular statistics would be used to obtain a measure of dispersion with this type of variable. However, in the current study, participants were asked to keep the end effectors as symmetrical as possible in an in-phase coordination mode. Therefore, in practice, the values were in the range of +90$^{o}$ and -90$^{o}$, which implied that normal distribution statistics could be used. Group data of mean CRP, SD CRP and movement time were submitted to separate mixed ANOVA with one repeated factor, divide (3 levels), and one independent factor, group (2 levels). Additionally, the mean jerk data were submitted to a mixed ANOVA with two repeated factors, arm (2 levels) and divide (3 levels), and one independent factor, group (2 levels). In cases where the sphericity assumption was violated, Greenhouse-Geisser adjustments were made. Fishers' LSD was used for post hoc analysis, and the alpha-level was set at 0.05. Effect size ($\omega^2$) data was calculated according to Field (2005) and standard error was reported to indicate the true mean variability.

**Results**

There was no significant difference between the groups for mean CRP (TD = -4.4 ± 3.3$^{o}$; SHCP = -0.3 ± 4.4$^{o}$) or movement time (TD = 3.01 ± 0.45 s, range = 1.45 – 7.82 s; SHCP = 3.50 ± 0.59 s, range = 1.43 – 9.66 s). This indicates that the children with SHCP were able to maintain a similar coordination pattern (mean CRP) as the TD children, and that both groups lead with the non dominant/more impaired arm. However, as seen in Fig. 3.2, children with SHCP exhibited significantly higher SD CRP [$F(1,20) = 22.67$, $p < .01$, $\omega^2 = .53$] compared to the TD children.

There were no significant differences between the divides for mean CRP (glass = -1.0 ± 2.8$^{o}$; screen = -2.9 ± 3.6$^{o}$; mirror = -3.0 ± 3.1$^{o}$) or movement time (glass = 3.10 ± 0.39 s, range = 1.43 – 9.66 s; screen = 3.39 ± 0.46 s, range = 1.43 –

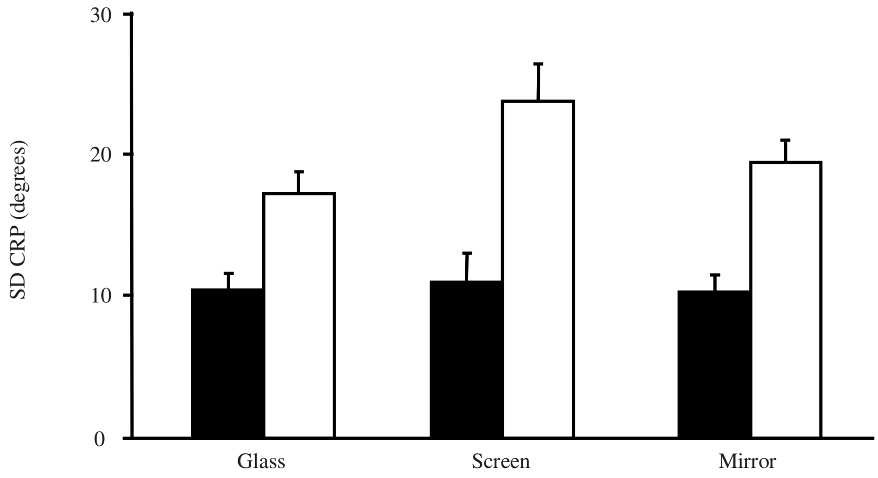
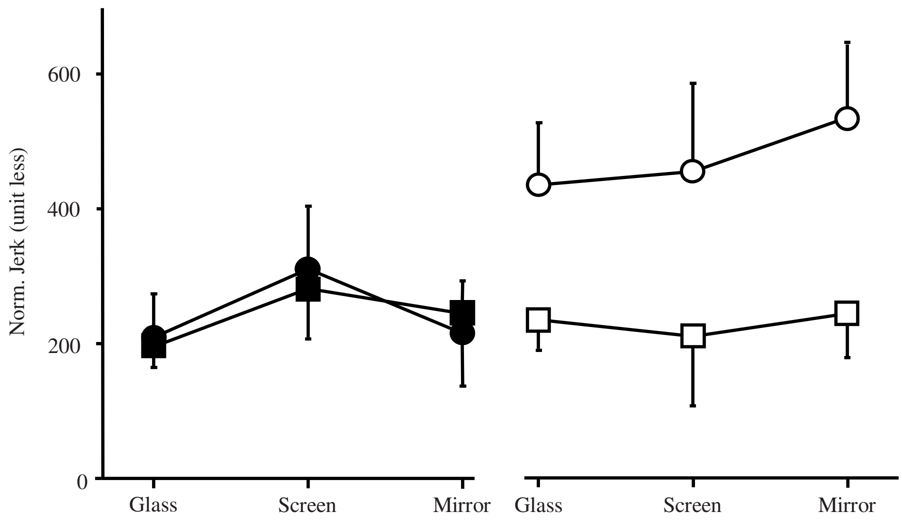



**Fig. 3.2:** Standard deviation of the continous relative phase of the control (solid) and the SHCP group (open) during the glass, screen and mirror condition of the ‘mirror box’. Error bars (SE) indicate true mean variability.

9.32 s; mirror = 3.28 ± 0.33 s, range = 1.45 – 8.07 s). Also, there was no significant group by divide interaction for these variables [all: $p > .49$]. However, there was a significant main effect of divide for SD CRP [$F(1.4,28.1) = 4.91$, $p < .05$, $\omega^2 = .20$], as well as a significant group by divide interaction [$F(2,40) = 3.4$, $p < .05$, $\omega^2 = .15$], indicating that the two groups responded differently to the 3 divides (see Fig. 3.2). Post hoc tests revealed that the variability of the coordination pattern (SD CRP) in the TD children was equal in all the conditions. In contrast, for children with SHCP, SD CRP was significantly higher in the screen condition compared to the glass and the mirror condition [$p < .01$ and $p < .05$, respectively]. Furthermore, SD CRP in the mirror condition did not differ significantly from the glass condition [$p > .23$].

Results for normalized jerk showed that the mean for one child with SHCP was twice the value of the group mean, hence this participant was considered as an outlier and excluded from the analysis. In the remaining data, there was no significant main effect of group or divide for normalized jerk in the medial/lateral direction or posterior/anterior direction [all: $p > .19$]. There was a significant main effect for arm [$F(1,19) = 16.8$, $p < .01$, $\omega^2 = .47$; $F(1,19) = 13.1$, $p < .01$, $\omega^2 = .41$, for medial/lateral and posterior/anterior direction, respectively], as well as a significant group by arm interaction [$F(1,19) = 15.7$, $p < .01$, $\omega^2 = .45$; F(1,19 = 11.4, $p < .01$, $\omega^2 = .38$;

a




b

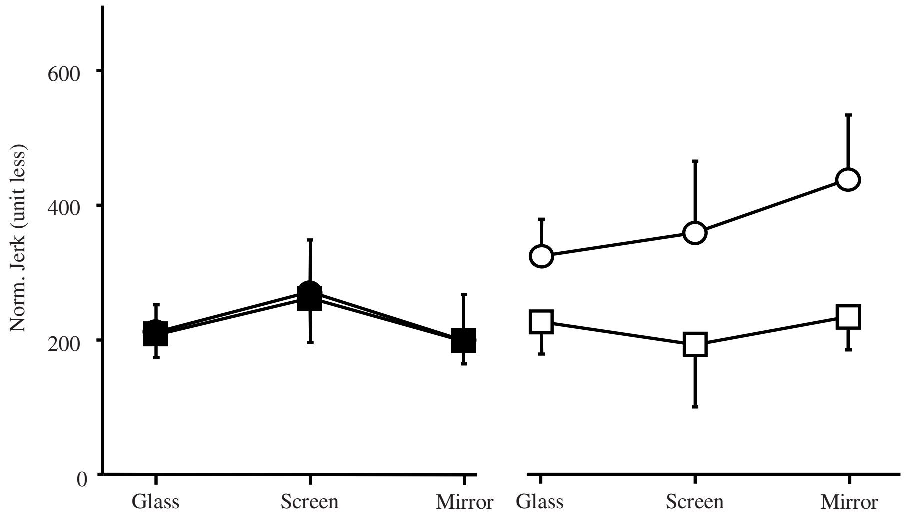



**Fig. 3.3:** Mean normalized jerk in the dominant/less impaired arm (squares) and non-dominant/more impaired arm (circles) for TD children (solid) and children with SHCP (open) during the glass, screen and mirror condition in the a) medial/lateral direction and b) posterior/anterior direction. Error bars (SE) indicate true mean variability.

see Fig. 3.3]. Post hoc analyses of the group by arm interaction revealed that normalized jerk in the more impaired arm of children with SHCP was significantly larger than in the less impaired arm in both the medial/lateral direction [$p < .01$; 230.6 and 475.4, respectively] and in the posterior/anterior direction [$p < .01$; 217.6 and 375.0, respectively]. In TD children, however, there was no difference between the dominant and non–dominant arm in the medial/lateral direction (240.5 and 244.8, respectively) or the posterior/anterior direction (223.2 and 228.6, respectively). No other significant interactions were found for normalized jerk [all: $p > .28$].

**Discussion**

The current experiment examined coordination of the upper limbs when children with SHCP and a TD age-matched control group performed a symmetrical bimanual movement under conditions of different visual feedback. Consistent with results from experiments that have examined bimanual reach and grasp tasks (Steenbergen et al., 1996; Sugden & Utley, 1995), it was found that for the first two cycles of a bimanual circular movement, children with SHCP were able to maintain a similar mean temporal coordination pattern (i.e., mean CRP and movement time) compared to an age-matched control group. However, children with SHCP showed greater variability of the coordination pattern (i.e., SD CRP) compared to the TD children, and exhibited increased normalized jerk in the more impaired arm compared to the less impaired arm. The level of bimanual variability exhibited by SHCP children in the current study was similar to that reported by Volman et al. (2002). In combination, therefore, these results confirm that while differences in bimanual movement capabilities exist between children with SHCP and TD children, for the first 2 complete cycles, children with SHCP can complete the overall goal of the task (i.e., symmetrical bimanual movements).

In addition to determining the underlying coordination of the upper limbs in these two groups, the current study also enabled us to investigate how this was affected by the availability of visual information from the less impaired and more impaired upper limbs. As expected, there was no difference in the measures of bimanual coordination as a function of visual feedback (i.e., divide) for the TD children (see Franz & Packman, 2004). For the SHCP children, however, despite there being no difference in mean temporal coordination pattern or movement time across the three conditions, there was an increase in interlimb movement variability in the opaque screen condition; bimanual coordination in the mirror condition did not differ from the glass condition. These results indicate that the SHCP children had difficulties maintaining a stable interlimb coupling when visual information of the impaired arm was absent. Furthermore, providing SHCP children with the opportunity to see a mirror reflection of their less impaired arm resulted in levels of movement variability similar to that when performing in the glass condition. The important point to note, therefore, is that while no beneficial effects of performing in the 'mirror box' were found (see Altschuler et al., 1999), there were also no negative effects of substituting the veridical information from the more impaired limb with a mirror reflection of the less impaired limb. Given that the visual feedback available in the mirror condition would have been the most unusual circumstance for children with SHCP (i.e., they perceived two less impaired arms), it will be important to next determine whether a more prolonged training protocol with the mirror could result in a reduced movement variability compared to the glass condition.

The effects of 'mirror box' therapy in individuals with hemiparesis have been explained based on central or peripheral mechanisms. While it is not the intention here to discriminate which of these explanations better explain our results, it is relevant to consider each of these underlying mechanisms. A possible explanation for the described observations might be sought within the organisation of the central nervous system. Garry et al. (2005) found that when typically developed adults viewed their unimanual movements through a mirror, the excitability of M1 area of the inactive contralateral arm increased beyond that produced by ipsilateral hand movements alone. This suggests that an increase in cross-talk could occur from the intact brain hemisphere towards the damaged brain hemisphere. Future research with transcranial magnetic stimulation and functional magnetic resonance imaging of children with SHCP whilst using the 'mirror box' might disclose further evidence to support the central mechanism explanation.

Alternatively, a possible peripheral mechanism involves a change in directed attention to the intact sensory feedback (i.e., vision) instead of distorted sensory feedback (i.e., proprioception). Indeed, for individuals with hemiparesis, it has been suggested that redirection of visual attention towards the sensory feedback of the more impaired arm might help individuals with hemiparesis to reduce movement disorders and future complications such as learned disuse (Sathian et al., 2000; Opila-Lehman et al., 1985). The 'mirror box' is thought to assist with the switch in attention because the visual signals received back from the superimposed image seen in the mirror correspond with the movements of the less impaired arm. In other words, an individual receives positive reinforced visual feedback from the superimposed image of intended movements (Ramachandran, 2005; Moseley, 2004). In line with this position, the work of Mechsner et al. (2001) shows that visual information is able to override muscular constraints when participants are instructed to perform highly complex bimanual coordination patterns (see also Tomatsu & Ohtsuki, 2005).

Although normalized jerk is not a direct measure for spasticity, it did present an opportunity to objectively quantify the movement difficulties that children with SHCP experienced in the more impaired arm. The greater amount of normalized jerk measured for the more impaired arm, confirms the detrimental asymmetric effect of SHCP. Additionally, in contrast to the interlimb movement variability, there were no differences for normalized jerk in the arms of children with SHCP between the different visual manipulations. This indicates that the motor behaviour of both the more and the less impaired arm did not change in the mirror condition, and therefore that the changes in movement variability in response to the visual manipulations cannot be explained by changes in normalized jerk of either arm alone. Direct measurement of the abnormalities of the upper limb neuromuscular activity during bimanual movement should be addressed with the use of electromyography in subsequent experiments.

Given the effect of handedness on the relative phase of bimanual coordination (Swinnen et al., 1996), it could be argued that the different distribution in hand dominance in the two groups (i.e., the children with SHCP were predominantly left hand dominant whilst the TD children were all right hand dominant) may have contributed to the findings of the present study. In previous research in adults, the dominant hand was demonstrated to be the leading limb in bimanual tasks with a smaller phase lag in left-handers than in right-handers (Franz, 2004; Franz et al., 2002; Amazeen et al., 1997; Swinnen et al., 1996). It therefore seems surprising that the participants in the current study tended to lead the bimanual movement with their non-dominant arm/more impaired arm. A possible explanation of this discrepancy may reside in the altered constraints imposed on arm movement (i.e., range of motion in the shoulder and elbow joints) due to the specific position of head, neck and, trunk that was required to perceive the visual illusion. In pilot data, it was found that when participants angled their head towards the side of their non-dominant/more impaired arm, a switch in arm lead occurred (i.e., the arm on the contralateral side of the divide lead the movement), although more research is needed to confirm this observation. In addition, it should be acknowledged that hand dominance in children with SHCP might well be the result of other and additional lateralizing factors (i.e., muscle dysfunction due to neurological damage) than in TD children. Previous research has suggested that bimanual control is different and less lateralized in left-handers (e.g., Swinnen et al., 1996). However, given the potential distinction in the origin and significance of hand dominance in children with SHCP and TD children, the impact of handedness on bimanual control in the current study is difficult to ascertain and has yet to be determined.

It is well reported that children affected by SHCP exhibit an increased muscle tone in certain antagonist muscle groups that affects the muscle stretch reflex and higher velocity-dependent resistance on one side of the body during motion (Miller, 2005). This study has suggested that these effects of SHCP might have played an important part in the observation that some children with SHCP could only produce 2 cycles before they switched to a different coordination mode (e.g., from inward to outward or from symmetrical to asymmetrical). It is worth considering, however, that another related explanation could lie in the adopted timing control strategy as shown by Zelaznik et al. (2005). In a similar task it was found that during the early stages of continuous circle drawing of adults, control of the movement rapidly transited from event-based (i.e., a temporal representation is part of the task goal) to emergent timing (i.e., explicit representation of the interval duration of the task is not required). It could be argued that children with SHCP have difficulties to adopt this emergent timing strategy where the movement is controlled on the basis of the task dynamics rather than specific time events. Future research is warranted to investigate if this event-based timing strategy was less optimal for this cyclic task and therefore a contributing factor for the fact that some children with SHCP could only perform 2 cycles.

In conclusion, the results from this exploration of acute effects on bimanual coordination show that the upper limb movement of children with SHCP is more variable than that of TD children. Additionally, children with SHCP show greater amounts of normalized jerk in the more impaired arm compared to the less impaired arm. The manipulation of visual information only affected movement variability in children with SHCP, which was significantly greater in the screen condition compared to the glass and mirror condition. These results are encouraging and warrant further investigation to establish if a period of sustained practice with the 'mirror box' has any long-term benefits on bimanual coordination, as well as positive transfer to daily life activities.

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# CHAPTER 4

## Assessment of neuromuscular activation of the upper limbs in children with spastic hemiparetic cerebral palsy during a dynamical task

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**Abstract**

The aim of this experiment was to investigate the neuromuscular activity and frequency content of the EMG signals recorded from the arm muscles in children with SHCP and TD children. It was found that children with SHCP during a bimanual circular movement had higher intensities of mean neuromuscular activity compared to TD children. Furthermore, the movement was characterised by longer phases of eccentric and concentric activity in children with SHCP, indicating more co-activation, especially in the more impaired arm. The EMG signals yielded a higher mean power frequency in all the muscles of the more impaired arm and the wrist and elbow flexors of the less impaired arm, which reflects a relatively higher contribution of type II muscle fibres compared to TD children. These observations suggest that in children with SHCP bimanual coordination requires higher EMG activity in the muscles of both arms. SHCP also seems to involve structural changes to the muscle properties and function, which differ between arms.

**Introduction**

Cerebral Palsy (CP) is a group of congenital neurological brain disorders, which affects 2 – 2.5 individuals per 1000 live births (Lin, 2003). A common form of CP is spastic hemiparetic cerebral palsy (SHCP), which is caused predominantly through unilateral damage to the motor cortex and / or pyramidal tract. There is evidence that a unilateral cerebral lesion also affects the body-side ipsilateral to the lesion (Yarosh et al., 2004; Wiley & Damiano, 1998). However, the unilateral damage causes children with SHCP to have a strong asymmetry between body-sides, which is predominantly manifested in irregular and jerky movements of the more impaired body-side compared to the less impaired side and the movements of typically developing (TD) children (Chapter 3).

Movement is caused by the contraction of skeletal muscles, which, in turn is affected by the properties of the muscle. These properties are traditionally divided into three main categories: (1) architectural properties, which are dependent on fascicle orientation (i.e., parallel or pennate), (2) the structural properties, reflected in fibre thickness, length and type, and (3) state of the muscle, defined by strength, fatigability and activation (i.e., as a synergist or an antagonist; Rozendal & Huijing, 1998; Wilmore & Costill, 1999). Although not always in similar detail, all three muscle properties have been investigated in children with SHCP. Recently, Mohagheghi et al. (2007) found that the pennation angle of the muscle fascicles in the gastrocnemius was similar between the body sides indicating similarity in muscle architecture. However, with respect to the muscle structure, the muscle fascicles' length and thickness at rest were smaller in the more impaired leg compared to the less impaired leg. Additionally, Wakeling et al. (2007) found that during walking the electromyography (EMG) signals of muscles in both legs of children with diplegic CP had higher mean power frequencies compared to TD children. According to Kupa et al. (1995) higher mean power frequencies in the EMG signals are caused by the predominant activation of thicker and faster conducting type II fibres compared to the thinner and slower conducting type I fibres. Therefore differences in mean power frequency may suggest a dissimilar distribution of muscle fibres and/or differential motor unit recruitment. A couple of studies have attempted to quantify muscle fibre distribution in the lower (Ito et al., 1996; Rose et al., 1994) and upper limbs (Pontén et al., 2005) of children with SHCP through muscle biopsy. The results, however, were inconclusive (for a review see Lieber et al., 2004) and were not directly related to movement in children with SHCP. Finally, with regard to the state of the muscle it was found that muscle strength was lower in the more impaired leg compared to the less impaired leg (Wiley & Damiano, 1998) and that co-activation was greater during knee extension in children with CP compared to TD children (Ikeda et al., 1998). Although the cause-effect relationship between muscle structure and state is unclear in children with SHCP, the findings above suggest that SHCP is accompanied by muscle properties that may account in part for the differences in muscle function, which in turn affects motor behaviour.

Previous research on muscle properties of children with SHCP has predominantly focussed on muscles in the lower extremities (Mohagheghi et al., 2007; Wakeling et al., 2007; Perry et al., 2001; Ikeda et al., 1998; Wiley & Damiano, 1998). In contrast to the upper extremities, which are mainly used for activities requiring more accurate movements such as grasping, holding and manipulating objects, the lower extremities are typically involved in weight bearing activities such as standing and walking. Given this task-related discrepancy, SHCP may affect the muscle properties (e.g. fibre distribution), activity and behaviour (e.g. the extent of spasticity and weakness) of the lower and upper limbs differently. Moreover, many individuals with SHCP compensate for the loss in functionality in their more impaired side by using it less frequently (Taub et al., 1998). Once a child with SHCP adopts this selective disuse strategy, they may end up in a negative spiral that can lead to an inhibition of functional recovery of the more impaired arm (Cauraugh & Summers, 2005). The selective disuse of the more impaired arm might in turn lead to a more prevalent distinction (i.e., asymmetry) between muscle properties of the more and the less impaired arm (Mohagheghi et al., 2007). Both factors (i.e., functional difference and potential disuse strategy) highlight the need for investigation into the effect of SHCP on the muscle properties between the arms.

On a kinematic level, increased jerkiness in the more impaired arm of children with SHCP already provided some indirect insight into the muscle function and asymmetry between upper limbs (Chapter 3). However, the relationship between neuromuscular activation and kinematic measures is non-linear (Requin et al., 1984) and EMG gives the opportunity to objectively and directly measure the effects of SHCP on muscular activation and structure.

The aim of this experiment was to investigate the intensity and frequency content of the EMG signals of both arms simultaneously in children with SHCP and

TD children. A bimanual symmetric circular movement was used because this required concurrent activation of homologous muscle groups providing the opportunity to compare the more impaired arm with the less impaired arm at the same time. In addition, this task involved movements that were not constrained to a single direction and encompassed both anterior-posterior and medial-lateral movements. Based on previous research in leg muscles, it was hypothesized that the SHCP would lead to higher intensities of mean neuromuscular activity in the more impaired arm compared to the less impaired arm, which in turn would have higher levels of intensities compared to the arm muscles in TD children. Moreover, it was expected that the higher intensities of mean neuromuscular activity found in the arm muscles of children with SHCP would be associated with excessive co-activation during the arm movement (Ikeda et al., 1998). Additionally, it was anticipated that higher mean power frequencies would be found between the muscles in the more impaired arm of children with SHCP compared to the muscles in the arms of TD children. However, it was predicted that the mean power frequencies would be similar between the muscles in the less impaired arm of children with SHCP and the muscles in the arms of TD children. Moreover, it was predicted that higher mean power frequencies would be found in the EMG signals from the muscles in the more impaired arm compared to the muscles in the less impaired arm in children with SHCP.

**Methods**

*Participants*

The participants with SHCP were 10 children (mean age 13.8 years, SD = 3.0 years, age range = 8 – 18 years, 7 males and 3 females) with mild (n = 8) and moderate (n = 2) SHCP. One participant was right-hand dominant (RHD) and the other 9 participants were left-hand dominant (LHD). For age-matched control participants, 12 TD children were selected from a pool of 20 who participated in a previous study (mean age 13.2 years, SD = 2.8 years, age range = 9 – 18 years, 9 males and 3 females, 12 RHD and 0 LHD). The individual characteristics of the children are presented in Table 4.1. Participants classified as TD were excluded from the study if they had any neuromuscular disorders, pain in either of their upper limbs, a visual impairment which was not corrected to normal, or could not adhere to the required task. The same exclusion criteria applied to the participants with SHCP,

**Table 4.1:** Information on the children with SHCP and their age-matched control(s).

| Participant | Age (Years) | Gender | More Impaired Arm | Severity | Aetiology | Matched Control Participant (Age / Gender / Arm Dominance) | |
|---|---|---|---|---|---|---|---|
| 1 | 16.3 | F | Left | Mild | $O_2$ shortage during birth | 14.8 / M / R | - |
| 2 | 17.1 | M | Right | Mild / Moderate | Cerebral haemorrhage | 16.7 / M / R | - |
| 3 | 8.7 | F | Right | Mild | Cerebral haemorrhage | 9.6 / M / R | 9.3 / M / R |
| 4 | 11.0 | M | Right | Mild | Meningitis just after birth | 10.0 / F / R | - |
| 5 | 12.2 | M | Right | Mild | Unknown | 12.4 / F / R | 12.8 / M / R |
| 6 | 13.2 | M | Right | Mild | Unknown | 14.0 / F / R | - |
| 7 | 17.4 | M | Right | Mild | $O_2$ shortage during birth | 17.2 / M / R | - |
| 8 | 14.3 | M | Right | Mild | Cerebral haemorrhage during birth & Meningitis just after birth | 14.6 / M / R | - |
| 9 | 11.1 | M | Right | Moderate | Cerebral haemorrhage during birth | 10.6 / M / R | - |
| 10 | 16.7 | F | Right | Mild | Cerebral haemorrhage during birth | 16.2 / M / R | - |

*Note.* Severity of the child's impairment was graded with a combination of the modified Ashworth scale (AS), functional independence measure for children (WeeFIM) and gross motor function classification system (GMFCS).

except that they had no history of a neuromuscular disorder other than SHCP. The experiment was conducted in accordance with the Declaration of Helsinki. Written informed consent was given by the participants' parents and written informed assent was obtained from all participants. The institutional research ethics committee approved all procedures.

*Materials and procedure*

In each hand, participants gripped a handle from an arm ergometer (871E, Monark Exercise AB, Vansbro, Sweden). Each handle was attached to the edge of a wooden disc with a radius of 0.10 m, which spun freely through $360^o$ around a vertical axis. The axes were fixed to a wooden plateau (width 0.60 m, depth 0.46 m, height 0.04 m) and were located 0.31 m apart. Participants sat on a stool at a table. The stool height was adjusted so that each participant sat comfortably with both feet flat on the floor, knees and elbows flexed to 90°. If a participant was unable to grip the handle because of physical impairment, the hand was placed on top of the handle by the experimenter[2].

Participants were asked to perform an inward symmetrical circular bimanual task (i.e. the right arm rotated anti-clockwise and the left arm rotated clockwise irrespective of hand dominance), requiring synchronized activation of homologous muscles in each arm during a single task. The discs were rotated continuously at a self-selected pace after the start instruction was given and until they were instructed to stop. The participants were also instructed to keep movement time (i.e., movement frequency) constant during the experimental trials. Three trials were recorded each lasting approximately 15 seconds. Prior to data collection, practice trials were conducted to familiarize the participant with the test setup. In order to keep the participants motivated, they were told that rotating the handles symmetrically would result in more points being scored, and at the end of the experiment they could trade the points for a small gift.

Superficial EMG was bilaterally recorded from the main muscles around the wrist, elbow and shoulder: flexor digitorum superficialis (FDS), extensor carpi

[2] A sheet of glass (width 0.06 m, depth 0.75 m, height 0.39 m), which was part of another supplementary experiment, was securely placed between the arms of the participants, which did not obscure their vision.

radialis brevis (ECRB), biceps brachii brevis (BBB), tricpes brachii longus (TBL), deltoideus pars anterior (DPA) and deltoideus pars posterior (DPP). A ground electrode was placed over the acromion on the side of the dominant hand. Pairs of disposable Ag/AgCl surface EMG electrodes (Blue Sensor Electrodes N, Ambu Inc., Glen Burnie, MD, USA) with a gel-skin contact, active detection area of 15 $mm^2$ for each electrode and a 20 mm centre to centre inter-electrode distance, were placed in parallel with the muscle fibre direction over the muscle bellies after cleaning and gentle abrasion of the skin. The EMG signals were amplified 20 times, high-pass pre-filtered at 10 Hz and AD-converted at 1000 Hz with a 22-bit resolution (Porti-17, Twente Medical Systems, Enschede, The Netherlands, input resistance $>10^{12}\Omega$, CMRR > 90 dB) and stored on a computer. The EMG signals were band-pass filtered with a zero lag 2$^{nd}$ order Butterworth filter between 10 and 400 Hz and then full-wave rectified.

Two serially-connected units, each containing three infrared cameras (3020 Optotrak, Northern Digital Inc., Waterloo, Canada), were used to measure the 3D position of relevant anatomical landmarks. Light emitting diodes were bilaterally attached to the skin with double-sided tape over the dorsal tuberculum of the radius (wrist), lateral epicondyle of the humerus (elbow), greater tubercle of the humerus (shoulder) and trochantor of the femur (hip). The EMG and motion capture computers were synchronised with a pulse signal.

*Data analysis*

Bilateral EMG recordings were analyzed from the first two cycles[3] of each trial because some children with SHCP could only produce 2 cycles before they changed to a different direction (e.g., outward) or a transition from a symmetric to an asymmetric coordination pattern occurred (i.e., both arms going clockwise or anti-clockwise). Moreover, for some of the children with SHCP, movement time only allowed them to complete 2 cycles within the allocated time of each trial, or the hand slipped of the handle at which point the trial was terminated. Overall, in the TD children group 1 out of 36 trials were excluded from analysis, whereas in the children

[3] The first two cycles were derived from the kinematic data from the wrist. Pilot studies showed that participants were able to maintain an anatomical neutral position of the wrist during the movement, which ensured reliable recordings.

with SHCP group 7 out of 30 trials were excluded from analysis. The duration of the 2 cycles was determined to enable calculation of movement time.

Typically, EMG amplitudes are scaled to activation levels recorded either during an isometric maximal voluntary contraction or a specified steady-state sub-maximal contraction. However, when comparing intensities of mean neuromuscular activity between patients with different pathologies (i.e., children with SHCP) to TD children, the method of normalization is likely to be unreliable in this patient population because their limitations inhibit maximal contractions, or their EMG amplitude during a steady-state sub-maximal task differs between groups (Smith et al., 2008; Van Dieën et al., 2003; Perry et al., 2001; Damiano et al., 2000). Therefore, to calculate the intensity of the mean neuromuscular activity of each muscle during the bimanual movement, the mean amplitude was calculated from the smoothed raw EMG signals (zero-lag $2^{nd}$ order low-pass Butterworth filter at 6 Hz).

To estimate the level of co-activation (i.e., eccentric and isometric activity) of the muscles around the elbow and shoulder joint during the arm movement, the kinematic and EMG data were combined. The bimanual movement was broken down into phases of eccentric, concentric and isometric activity or inactivity (Fig. 4.1). For example, if the elbow joint angle increased, the activity of the BBB muscle (elbow flexor) was classed as eccentric. If the elbow joint angle decreased, the activity of the BBB muscle was classed as concentric. The activity of the muscle depended on orientation of the muscle around the joint (see Table 4.2). If the muscle was active but there was no change in the joint angle the activity was classed as isometric. Based on the assumption that a purposeful activation of a muscle causes an increase in the EMG signal, particularly in the frequency range of 0 – 160 Hz (Winter, 1979), the active/inactive threshold for muscle contraction was determined with the following formula:

$$T = 15 + 1.5R$$

where T is the active/inactive threshold value, R is the mean value of the EMG signal above 160 Hz and the constants are derived from Perry et al. (2001). A muscle was considered active if the smoothed raw EMG signal was above the threshold level, otherwise the muscle was considered inactive. The phases of activity/inactivity were expressed as a percentage of the overall movement (i.e., the 2 cycles). Additionally, to

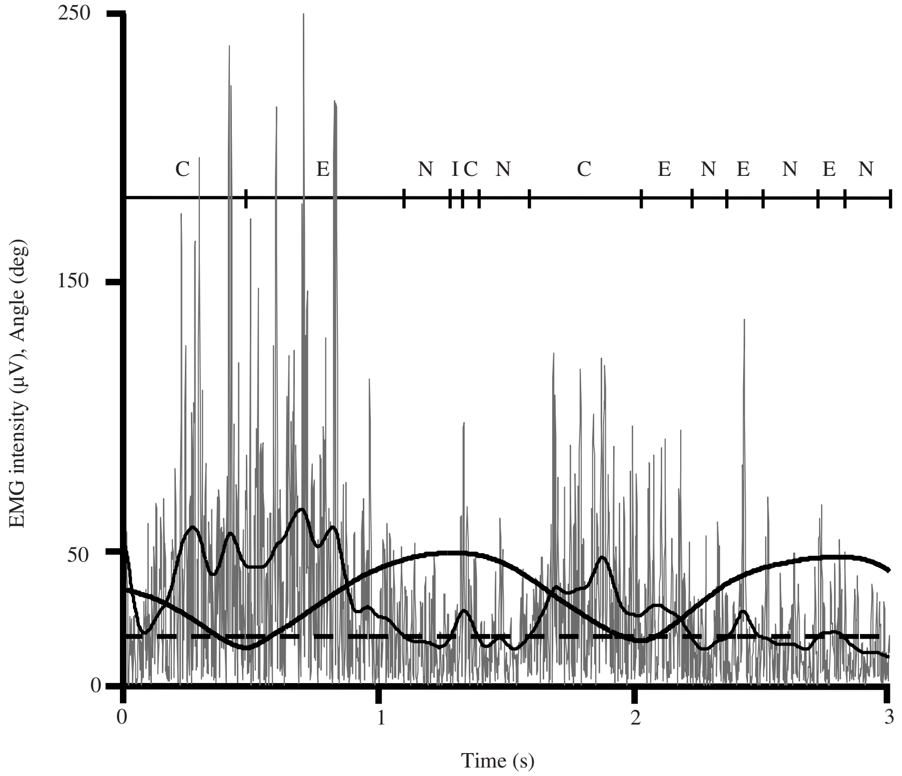


**Fig. 4.1:** Data from a representative trial showing the combination of rectified EMG activity (grey) from the deltoideus pars posterior and shoulder angle (thick) of a TD child's dominant arm. The smoothed EMG (thin) and active/inactive threshold for muscle contraction (dashed) is also depicted. Muscle activation is classed as eccentric (E), concentric (C), isometric (I) and inactivity (N).

determine SHCP related adaptations in muscle structure, the mean power frequency of each EMG signal was calculated. The mean power frequency was determined by using the fast Fourier transformation to create a total power spectrum from which the mean power frequency was computed.

*Statistical analysis*

For each muscle a mixed ANOVA with two repeated factors, arm (2 levels), and one independent factor, group (2 levels), was used to compare the children with SHCP with the TD age-matched control group on movement time, intensities of mean neuromuscular activity and mean power frequencies. Additionally, for the muscles around the elbow and shoulder (BBB, TBL, DPA and DPP) a mixed ANOVA with two repeated factors, arm (2 levels), and one independent factor, group (2 levels), was used to compare the children with SHCP with the TD children on the distribution of the nature of muscle activation (i.e., eccentric, concentric and isometric activation and inactivation). Fishers' LSD was used for post hoc analysis. The alpha-level was set at 0.05.

**Table 4.2:** Definition of eccentric and concentric activation for the biceps brachii brevis (BBB), triceps brachii longus (TBL), deltoideus pars anterior (DPA), deltoideus pars posterior (DPP) when the angle of the elbow (i.e., angle between forearm and upper arm) and shoulder (i.e., angle between upper arm and trunk) increases and decreases.

| | Elbow angle | |
|---|---|---|
| | Increase | Decrease |
| BBB activity | Eccentric | Concentric |
| TBL activity | Concentric | Eccentric |

| | Shoulder angle | |
|---|---|---|
| | Increase | Decrease |
| DPA activity | Concentric | Eccentric |
| DPP activity | Eccentric | Concentric |

## Results

*Movement time*

There was no significant difference between the groups for movement time (TD = 2.93 ± 0.97 s, range = 1.47 – 5.38 s; SHCP = 3.24 ± 2.36 s, range = 1.37 – 9.60 s; $F = 1.30$; $p = 0.27$). This indicates that the children with SHCP had a similar movement frequency as the TD children, which confirmed that other analyses could be conducted.

*Intensity of mean neuromuscular activity*

There was a significant main effect of group for the mean neuromuscular activity in the FDS, BBB and TBL muscles (Fig. 4.2; all: $F > 7.56$; $p < 0.01$), which showed that children with SHCP had higher levels of mean neuromuscular activity. Additionally, there was a significant group by arm interaction for the neuromuscular activity in the TBL only ($F = 4.85$; $p < 0.05$). Post hoc tests revealed that the mean neuromuscular activity of the TBL in both arms in TD children was equivalent ($p > 0.77$). In contrast, for children with SHCP, mean neuromuscular activity of the TBL was significantly higher in the more impaired arm compared to the less impaired arm ($p < 0.05$) and compared to the TBL activity in both arms of TD children ($p < 0.01$).

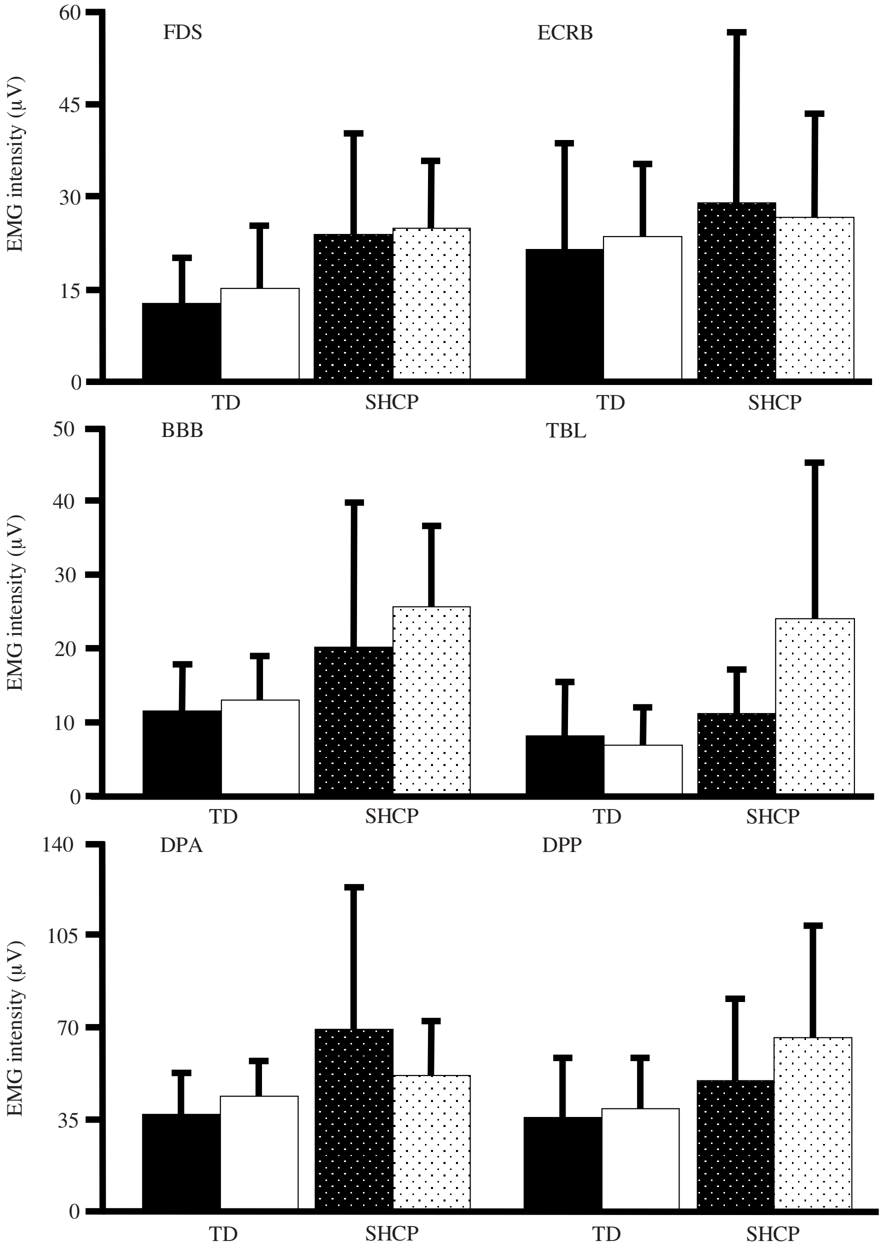


**Fig. 4.2:** Mean and SD of the raw EMG intensity for the flexor digitorum superficialis (FDS), extensor carpi radialis brevis (ECRB), biceps brachii brevis (BBB), triceps brachii longus (TBL), deltoideus pars anterior (DPA), deltoideus pars posterior (DPP) in the dominant/less impaired arm (black) and non-dominant/more impaired arm (white) of the TD children (non-dotted) and children with SHCP (dotted).

In sum, this indicates that for the children with SHCP the mean neuromuscular activity was similar in both the more and less impaired arm in the FDS and BBB muscles, but was still significantly higher in 3 out of the 6 muscles than in TD children.

*Muscle activation expressed as a percentage of the overall movement*

The analysis of muscle activation around the elbow and shoulder joints, expressed as a percentage of the overall movement, gives a more detailed insight into the neuromuscular activation pattern during the movement. It showed, as can be seen in Table 4.3, that eccentric muscle activation was significantly higher in the children with SHCP for BBB, TBL and DPP (all: $F > 4.91$; $p < 0.05$) compared to TD children. Additionally, eccentric muscle activation was significantly higher in the non-dominant/more impaired arm for the BBB ($F = 16.53$; $p < 0.01$) compared to the dominant/less impaired arm. More importantly, however, there was a significant group by arm interaction for the BBB and TBL (both: $F > 4.80$; $p < 0.05$). Post hoc tests revealed that the eccentric activity of the BBB and TBL muscles in both arms of TD children was similar ($p > 0.62$). In contrast, for children with SHCP, percentage of eccentric activity in the BBB and TBL muscles was significantly higher in the more impaired arm compared to the less impaired arm (both: $p < 0.05$) and compared to the arms of the TD children (all: $p < 0.01$). This indicates a higher percentage of the total activation period involved co-activation in these particular muscles of the more impaired arm. However, percentage of eccentric activity in the BBB and TBL muscles of the less impaired arm in children with SHCP was similar compared to the arms of the TD children (all: $p > 0.12$).

Likewise, concentric muscle activation was significantly higher in the children with SHCP for the BBB and TBL (both: $F > 4.95$; $p < 0.05$) compared to TD children. Additionally, a significantly higher amount of concentric muscle activation was found in the non-dominant/more impaired arm for the BBB and DPP (both: $F > 4.98$; $p < 0.05$) compared to the dominant/less impaired arm, which was most likely caused by the higher amount in the more impaired arm of children with SHCP (see Table 4.3). This group by arm interaction was significant for the TBL ($F = 6.24$; $p < 0.05$). Post hoc tests revealed that the concentric activity of the TBL was similar in both arms of the TD children ($p > 0.41$). For children with SHCP, percentage of concentric activity in the TBL was significantly higher in the more impaired arm compared to the less

**Table 4.3:** Mean value and SD of percentage muscle activity during the movement task for the biceps brachii brevis (BBB), triceps brachii longus (TBL), deltoideus pars anterior (DPA), deltoideus pars posterior (DPP) in the dominant/less impaired (dom) arm and the non dominant/more impaired (non – dom) arm of the TD children (TD) and children with SHCP (SHCP). Muscle activity is defined as: eccentric, concentric, isometric and inactive.

| BBB (% Muscle activity) | | | | |
|---|---|---|---|---|
| | Eccentric[a1,b1,c1] | Concentric[a2,b2] | Isometric[a1] | Inactive[a2,b2,c2] |
| TD dom | 6.2 ± (8.6) | 11.0 ± (10.9) | 0.3 ± (0.5) | 82.5 ± (19.3) |
| TD non - dom | 6.4 ± (6.8) | 13.4 ± (9.7) | 0.2 ± (0.3) | 80.0 ± (16.0) |
| SHCP dom | 11.8 ± (12.5) | 15.5 ± (17.2) | 0.4 ± (0.4) | 72.3 ± (27.9) |
| SHCP non - dom | 36.1± (19.0) | 28.3 ± (13.2) | 2.4 ± (3.8) | 33.2 ± (31.4) |

| TBL (% Muscle activity) | | | | |
|---|---|---|---|---|
| | Eccentric[a2,c1] | Concentric[a1,c1] | Isometric | Inactive[a2,c1] |
| TD dom | 3.7 ± (8.0) | 6.0 ± (8.6) | 0.1 ± (0.1) | 90.2 ± (16.3) |
| TD non - dom | 1.9 ± (4.9) | 3.6 ± (8.5) | 0.2 ± (0.5) | 94.3 ± (13.6) |
| SHCP dom | 8.5 ± (7.9) | 10.3 ± (10.6) | 0.3 ± (0.4) | 80.9 ± (17.4) |
| SHCP non - dom | 18.6 ± (15.9) | 18.8 ± (15.3) | 1.8 ± (3.4) | 60.8 ± (32.1) |

| DPA (% Muscle activity) | | | | |
|---|---|---|---|---|
| | Eccentric | Concentric | Isometric | Inactive |
| TD dom | 27.3 ± (13.0) | 38.0 ± (7.6) | 2.3 ± (4.4) | 32.4 ± (19.6) |
| TD non - dom | 31.0 ± (11.1) | 43.0 ± (5.0) | 1.1 ± (0.6) | 24.9 ± (14.4) |
| SHCP dom | 34.5 ± (16.5) | 42.7 ± (16.1) | 1.2 ± (0.9) | 21.6 ± (28.8) |
| SHCP non - dom | 38.0 ± (11.2) | 44.4 ± (10.0) | 2.6 ± (3.7) | 15.0 ± (12.5) |

| DPP (% Muscle activity) | | | | |
|---|---|---|---|---|
| | Eccentric[a1] | Concentric[b1] | Isometric | Inactive |
| TD dom | 24.1 ± (17.3) | 32.4 ± (15.0) | 1.7 ± (3.1) | 41.8 ± (32.1) |
| TD non - dom | 28.5 ± (17.2) | 38.1 ± (14.5) | 1.0 ± (0.6) | 32.4 ± (28.9) |
| SHCP dom | 36.8 ± (17.7) | 33.1 ± (14.3) | 1.2 ± (1.1) | 28.9 ± (28.1) |
| SHCP non - dom | 40.8 ± (14.0) | 42.7 ± (8.0) | 2.6 ± (3.7) | 13.9 ± (17.6) |

[a] Significant difference between groups.
[b] Significant difference between arms.
[c] Significant interaction between groups and arms.
[1] Represents significant differences ($p < 0.05$).
[2] Represents significant differences ($p < 0.01$).

impaired arm ($p < 0.05$) and compared to the arms of the TD children (both: $p < 0.05$). However, percentage of concentric activity in the TBL muscles was similar in the less impaired arm of children with SHCP compared to the arms of the TD children (both: $p > 0.15$). While a higher percentage of isometric contraction was found in the BBB muscle of children with SHCP compared to the TD children ($p < 0.05$), the overall percentage of isometric activation of all muscles was low (all: < 2.7%).

Finally, muscle inactivity was significantly higher in TD children for the BBB and TBL (both: $F > 8.43$; $p < 0.01$) compared to children with SHCP. Additionally, muscle inactivity was higher in the dominant/less impaired arm for BBB ($F = 11.77$; $p < 0.01$) compared to the non-dominant/more impaired arm. More importantly, however, there was a significant group by arm interaction for the BBB and TBL (both: $F > 6.29$; $p < 0.05$). Further analysis revealed that the percentages of muscular inactivity of the BBB and TBL of both the arms in TD children was similar ($p > 0.53$). In contrast, for children with SHCP, percentage of inactivity in the BBB and TBL was significantly lower in the more impaired arm compared to the less impaired arm (both: $p < 0.01$) and compared to the arms of the TD children (all: $p < 0.01$). Again, percentage of inactivity in the BBB and TBL muscles was similar in the less impaired arm of children with SHCP compared to the arms of the TD children (both: $p > 0.13$).

*Mean power frequencies*

There was a significant main effect of group for the mean power frequencies in all the muscles except ECRB (all: $F > 4.44$; $p < 0.05$) and a significant main effect of arm for the ECBR and TBL (both: $F > 9.39$; $p < 0.01$). More importantly, as seen in Table 4.4, there was a significant group by arm interaction for all the muscles except BBB (all: $F > 4.15$; $p < 0.05$). Post hoc tests revealed that the mean power frequencies of all muscles in the arms of TD children were similar ($p > 0.15$). However, for children with SHCP, the mean power frequencies of the more impaired arm were significantly higher compared to the TD children's muscles in the FDS, ECBR, TBL, DPA and DPP (all: $p < 0.05$). Additionally, the mean power frequencies were significantly higher in the more impaired arm compared to the less impaired arm of children with SHCP for the ECBR, TBL, DPA and DPP (all: $p < 0.05$). In sum, this indicates that for the children with SHCP the mean power frequencies of the more and less impaired arm in the FDS and BBB muscles were similar.

**Table 4.4:** Mean value and SD of the mean power frequency during the movement task for all the measured muscles in the dominant/less impaired (dom) arm and the non dominant/more impaired (non – dom) arm of the TD children (TD) and children with SHCP (SHCP). Additionally, the main effects and interactions (p-values) for group and arm are reported.

| | TD Dom | TD Non-Dom | SHCP Dom | SHCP Non-Dom | Group | Arm | Group x Arm |
|---|---|---|---|---|---|---|---|
| FDS | 128 ± 10 | 123 ± 15 | 131 ± 10 | 141 ± 21 | 0.04† | 0.42 | 0.05† |
| ECRB | 138 ± 8 | 136 ± 9 | 133 ± 10 | 148 ± 11 | 0.27 | 0.01† | < 0.01† |
| BBB | 109 ± 9 | 103 ± 10 | 113 ± 9 | 113 ± 10 | 0.04† | 0.25 | 0.34 |
| TBL | 112 ± 12 | 111 ± 8 | 114 ± 7 | 130 ± 12 | 0.01† | < 0.01† | < 0.01† |
| DPA | 107 ± 10 | 102 ± 10 | 109 ± 9 | 117 ± 15 | 0.03† | 0.50 | 0.01† |
| DPP | 102 ± 10 | 100 ± 6 | 103 ± 9 | 116 ± 19 | 0.05† | 0.09 | 0.02† |

*Note*. FDS, flexor digitorum superficialis; ECRB, extensor carpi radialis brevis; BBB, biceps brachii brevis; TBL, tricpes brachii longus; DPA, deltoideus pars anterior; DPP, deltoideus pars posterior.
† Represents significant differences ($p < 0.05$).

**Discussion**

The aim of this experiment was to investigate the neuromuscular activity and frequency content of the EMG signals recorded from the arm muscles in children with SHCP and TD children. The current study found that for the first two cycles of a bimanual circular movement, children with SHCP generally had higher intensities of mean neuromuscular activity compared to TD children. Interestingly, intensities of mean neuromuscular activity in the more and less impaired arm in children with SHCP were similar. Subsequent analysis, with regard to the nature of muscular activity, showed that children with SHCP had longer phases of eccentric and concentric activity and, consequently, shorter phases of muscular inactivity in the muscles around the elbow. This was predominantly prevalent in the muscular activation pattern in the more impaired arm of children with SHCP. In this group, higher mean power frequencies in the FDS and BBB were observed in both arms, whereas higher mean power frequencies in the other muscles were only observed in the more impaired arm. In spite of the asymmetric clinical nature of SHCP, these results confirm that bimanual movements of the more and less impaired arm are characterized by increased but similar neuromuscular intensities, which suggests bilateral coupling between the arms. In contrast, the asymmetry was reflected in the mean power frequency pattern, however not in all muscles. These results might be explained by a complex interaction between the clinical characteristics of SHCP and external factors.

The difference between children with SHCP and TD children for the intensities of mean neuromuscular activity was most pronounced in the distal muscles (i.e., muscles around the wrist and elbow) compared to the proximal muscles (i.e., muscles around the shoulder). Additionally, children with SHCP had longer phases of eccentric and concentric activation of the flexor and extensor of the elbow joint, suggesting increased co-activation, which was most pronounced in the more impaired arm of children with SHCP. The increased neuromuscular intensities and percentage of concentric activity of the distal arm muscles in the children with SHCP might be a reflection of a reduction in muscle strength, especially in the more impaired arm, which was previously suggested with respect to leg muscles in children with spasticity (Wiley & Damiano, 1998). Alternatively, the increased neuromuscular intensities in the elbow flexors and extensors and concomitant rise in co-activation may also be the result of a need to stabilize joints that are less involved in the task. Some task-dependent co-activation is normal (Ikeda et al., 1998), but excessive increases in co-activation is suggested to be a useful compensatory strategy (Selen et al., 2005; Van Dieën et al., 2003) for the neurological and muscular deficiencies that children with SHCP experience. Higher levels of co-activation increases joint stability (Feltham et al., 2006) and joint impedance, which, in turn, enhance movement accuracy (Van Galen & Schomaker, 1992; Van Galen & De Jong, 1995; Selen et al., 2006a; 2006b). This allows the motor system to respond more quickly to (unexpected) perturbations, which are likely to be present in children with SHCP due to irregular and jerky movements of the more impaired arm (Damiano et al., 2000). Therefore, the excessive co-activation in children with SHCP is probably the result of a trade-off between executing the bimanual circular movement and increasing movement accuracy by reducing any (unexpected) inappropriate movements of the more affected arm influenced by compromised reciprocal reflex-activity. However, the (excessive) co-activation is likely to increase energy expenditure, which, in turn, may result in a quicker onset of muscular fatigue.

A further notable finding of this study was the longer activity period of shoulder muscles compared to the elbow muscles. On average the DPA and DPP muscles were active 81.7% and 78.7% of the movement time in children with SHCP and 71.3% and 62.9% in TD children. On the other hand, the BBB and TBL muscles were active for only 47.3% and 29.2% in children with SHCP and 18.8% and 7.8% in TD children. The shoulder muscle activity appears to be more continuous, which might be explained by the need to stabilize the shoulder joint against the effects of gravity. In contrast, the elbow muscle activity seems to be more intermittent. The large inter-group differences between the duration of the elbow activity (28.5% and 21.4% for BBB and TBL, respectively) again indicate the discrepancy in co-activation between the two groups.

Next to these differences with regard to neuromuscular intensities, another important group difference was found for the mean power frequencies in the EMG signals from the muscles. Similar to the observations made by Wakeling et al. (2007) with respect to the leg muscles of children with CP, higher mean power frequencies were found in the children with SHCP, especially in the more impaired arm. The high-frequency components of the EMG spectrum have been suggested to be a reflection of the high-frequency content of action potentials generated by the fast fibre types, whereas the slow fibre types generate low-frequency action potentials (Bear et al., 2001). Therefore, the higher mean power frequency values for the muscles in the more impaired arm of children with SHCP in the current study might indicate that during the bimanual movement more fast-twitch muscle fibres (i.e., type II muscle fibres) were activated in children with SHCP compared to TD children (Kupa et al., 1995). This phenomenon may have been caused by systematic atrophy of type I muscle fibres in the more impaired arm (Lieber et al., 2004). Alternatively, these higher mean power frequency values might indicate that larger motor units, which generally contain fast fibre types (i.e., size principle; Bear et al., 2001), were active during the execution of this bimanual task. This is also reflected in the higher neuromuscular intensities but given the different pattern of EMG intensity and mean power frequency in relation to the less and more impaired arm, higher mean power frequencies are not just a linear function of higher EMG intensity.

For instance, in the wrist and elbow flexors (FDS and BBB) a symmetrical pattern was found for both the EMG intensities and the mean power frequencies between the more and less impaired arm in children with SHCP. Here the mean power frequencies (higher relative activation of type II fibres) might be a reflection of larger motor units being activated, because a higher mean neuromuscular intensity was also observed. This would suggest that unilateral brain damage results in changes to the motor control of not only the contralateral body-side but also the ipsilateral side

(Yarosh et al., 2004; Wiley & Damiano, 1998). Yarosh et al. (2004) hypothesized that, at a cortical level, unilateral damage could alter the excitability of the intact brain hemisphere because it takes over functions from the damaged brain area. This, in turn, could result in changes to descending signals from that intact hemisphere and may contribute to the arms being more bilaterally coupled with each other than in a typical population.

However, in the other muscles an asymmetrical pattern was found for the mean power frequencies (i.e., the mean power frequency was greater in the more impaired arm than in the less impaired arm), while the EMG intensities showed a symmetrical pattern, except for TBL. This is in contrast to the concurrent EMG intensity and the mean power frequency patterns for the wrist and elbow flexors. Because the increases in EMG intensity in the less impaired arm were not accompanied with an increase in mean power frequency, recruitment of motor units containing relative more type II muscle fibres may not be the exclusive explanation for the increased mean power frequencies in the more impaired arm. Additional factors, such as the presumed disuse of the more impaired arm, which may cause changes to the muscle structure (i.e., atrophy of muscle fibres and or increased distribution of type II muscle fibres), might contribute to the observed increase in mean power frequencies in the more impaired arm. This supports the notion that although SHCP has a neural origin, with the primary lesion being in the central nervous system, significant structural changes may occur to the skeletal muscle, which are secondary to the lesion (Pontén et al., 2005). In summary, the characteristics of muscle function in children with SHCP, which affects motor behaviour, seem to be the result of a complex interaction between primarily neurological and secondary external factors.

It could be argued that the current observations merely refer to the initiation of the movement because only the first 2 cycles were included. Analysis of the task during a more prolonged ‘steady state’ (i.e., 5 cycles or more) would have been preferred but the motor difficulties of the children with SHCP did not allow some of the participants to sustain or even attain a ‘steady state’ of the movement task. Different values for the percentage of muscle activation might have been found during a more prolonged ‘steady state’ movement task. However, the structural properties of the muscles, measured with the mean power frequencies, would not likely have been different.

In conclusion, this study showed that the children with SHCP had an increase in neuromuscular intensities in both the arms during a symmetrical bimanual task compared to TD children. Additionally, children with SHCP had a higher percentage of co-activation in the muscles around the elbow, which was predominantly manifested in the more impaired arm. Finally, higher mean power frequencies were found in the EMG signals of the wrist and elbow flexors in both arms and in the other muscles of only the more impaired arm in children with SHCP. These observations appear to indicate that during bimanual coordination, children with SHCP have higher levels of neuromuscular activation than TD children but still comparable between body-sides. However, additional factors such as changes to muscles structure do differ in nature between body-sides.

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# CHAPTER 5

## The ‘mirror box’ illusion: Effect of visual information on neuromuscular activation during bimanual coordination in children with spastic hemiparetic cerebral palsy

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**Abstract**

The study examined neuromuscular activation during bimanual coordination in children with spastic hemiparetic cerebral palsy (SHCP) and typically developing (TD) children under three conditions of visual feedback created by placing a glass screen, opaque screen or a mirror ('mirror box') between the arms. The 'mirror box' creates a visual illusion, which gives rise to a visual perception of a zero lag, symmetric movement between the two arms. Children with SHCP exhibited higher levels of mean neuromuscular activity compared to TD children. While the EMG intensities were similar for the more and less impaired arm, the periods of activation in the elbow muscles of the more impaired arm tended to be longer. Although manipulation of visual information did not affect the neuromuscular activation in TD children, EMG intensities in the shoulder muscles of children with SHCP were lower when veridical visual feedback was absent (i.e., screen and mirror condition). Similar attenuating effects of the mirror were found for the relative durations of eccentric and concentric activity in the elbow muscles. These findings indicate that the movement difficulties in children with SHCP may be caused by a discrepancy between actual visual feedback and the internal efference copy of a movement. Removing or replacing the visual information of the more impaired arm with a mirror reflection of the less impaired arm seems to improve their motor behaviour during interlimb coupling.

**Introduction**

Cerebral palsy (CP) is a group of congenital neurological disorders, which can be acquired between conception and up to 2 years post-natal (Miller, 2005). The precise prevalence of CP is difficult to determine but it is generally accepted at 2 – 2.5 per 1000 live births (Lin, 2003). A common form of CP is spastic hemiparetic cerebral palsy (SHCP), which is caused predominantly through unilateral damage to the motor cortex and/or pyramidal tract (Miller, 2005). A key feature of SHCP is spasticity of the muscles on the contralateral body-side of the neurological lesion. Spasticity is defined as an increase in the sensitivity of the normal stretch reflex in addition to a velocity-dependent increase in resistance to motion (Miller, 2005; Lance, 1980). Additionally, individuals with SHCP have limitations in proprioceptive feedback from the extremities (Van Der Weel et al., 1995) and as a result of these features the movements of the impaired arm are often slow and jerky (cf. Steenbergen et al. (2008) for an extensive overview). Furthermore, higher levels of co-activation are observed during the performance of isometric knee contractions, hip/knee flexion in supine position or walked at a self-selected comfortable speed (Wakeling et al., 2007; Perry et al., 2001; Ikeda et al., 1998). While a unilateral cerebral lesion has greatest impact on the contralateral body-side, it has been reported that movement of limbs on the ipsilateral side to the lesion is also mildly impaired (Van Der Weel et al., 1995). Still, it is notable that there is a strong asymmetry between body sides in individuals with SHCP, and hence the less impaired limb is often used as a 'control' against which the more impaired limb can be compared (Steenbergen et al., 2008).

A common form of intervention to improve the functional movement of the more impaired arm is bilateral movement rehabilitation. In this approach, individuals are asked to move both limbs together in a symmetrical fashion. By doing so, the natural tendency to synchronize movement frequency, amplitude and direction of the arms is exploited (Cauraugh & Summers, 2005). Previous research found that when children with SHCP perform such tasks, a reduction in asymmetry between the arm movements was observed (Steenbergen et al., 2008; Volman et al., 2002; Utley & Sugden, 1998; Sugden & Utley, 1995). For instance, when children with SHCP drew symmetrical circles with both hands, the temporal variability between the arms decreased and an improvement in the smoothness of the movements was observed in the more impaired arm (Volman et al., 2002). These findings suggest that movement of the more impaired limb is adaptable and that this is at least partially based on positive transfer from the less impaired arm during bimanual movement (Steenbergen et al., 2008; Utley et al., 2004; Volman et al., 2002).

Traditionally it was thought that motor commands limit the ability to perform bimanual coordination with an 1:1 ratio between the arms (i.e., the arms move with a similar velocity). However, it was shown that manipulation of visual information can also exert an influence (Mechsner et al., 2001; Shea et al., 2008). For example, it was found that typically developed adults were able to easily perform highly complex bimanual movements (i.e., ratio of 4:3, 2:1 and 3:2 between the arms) when visual feedback was manipulated to represented a simple 1:1 circular ratio between the arms (Mechsner et al., 2001). In line with these findings, previous studies showed that replacing actual visual feedback of an impaired (after stroke; Stevens & Stoykov, 2004; 2003; Altschuler et al., 1999) or absent limb (after amputation; Ramachandran et al., 1995) with a mirror reflection of the non-impaired contralateral limb has the capacity to relieve adverse effects of the condition (i.e. paralysis and spasms) during motion. According to Ramachandran (2005), the paretic and/or spastic movement in these populations is at least partially 'learned' through an atypical interaction between the internal copy of the motor commands sent by the central nervous system to the arms (i.e., efference copy) and the signals relayed back from the peripheral senses to the brain (i.e., afferent feedback; Von Holst, 1954). In individuals without movement impairment, motor commands sent from the premotor and motor cortex to perform an action are typically damped by sensory feedback. However, when the movement is impaired, a discrepancy between the sensory feedback and the centrally generated efference copy of the motor commands causes the following motor output to be amplified, which is suggested to further deteriorate motor performance. This 'vicious circle' may be interrupted by reconciling (visual) sensory feedback to the efference copy using the mirror reflection of the non-impaired arm superimposed over the affected arm (Ramachandran, 2005). The observations and proposed underlying mechanism raise the question as to whether similar adversities may play a role in the behaviour of children with SHCP. Whilst it is widely accepted that the primary source of spasticity in SHCP resides in cortical and pyramidal defects, the above findings demonstrate that the contribution of perceptual factors on movement needs to be investigated. More specifically, it has to be examined if a visual manipulation that removes the incongruity between actual visual feedback and the efferent copy has the potential to reduce the adverse effects related with SHCP, e.g. increased levels of neuromuscular co-activation and the associated temporal inconsistency during a bimanual coordination task.

In Chapter 3 insight into the kinematic aspects of this question was gained. Bimanual coordination of children with SHCP was examined under different conditions of visual feedback created by placing a glass screen, opaque screen or a mirror ('mirror box') between the arms. In the mirror condition, the reflection of the less impaired arm became a superimposed image over the more impaired arm. When children with SHCP were asked to perform a continuous bimanual symmetrical circle drawing task, it resulted in an illusory visual perception of a zero lag, symmetric movement between two less impaired arms. The study showed that the temporal variability between the arms was significantly higher when visual information of the more impaired arm was absent (i.e., opaque screen condition), compared to the glass condition where visual information was available of both arms and the mirror condition. These results indicate that the children with SHCP had difficulties maintaining a stable interlimb coupling in a condition where the more impaired arm was occluded from view. Furthermore, providing children with SHCP with the opportunity to see a mirror reflection of their less impaired arm resulted in levels of temporal variability similar to that when performing in the glass condition. While no beneficial effects were found when performing the bimanual task in the mirror compared to the glass condition as shown by Altschuler et al. (1999) and Ramachandran et al. (1995), the brief exposure to the mirror did influence the motor behaviour of the arms. At this stage however, it is unclear whether the effects of the mirror were a function of direct peripheral processes of perception-action coupling (such as an increased level of visual attention caused by the awareness of the mirror illusion), or by a central mechanism, involving the interference of the motor commands' efference copy and afferent signals as suggested by Ramachandran (2005). An investigation into the effects of the mirror on neuromuscular activation will enhance the understanding of the underlying mechanisms. This is particularly important as changes in neuromuscular activation do not necessarily correspond directly to differences in motor coordination (Requin et al., 1984; Bernstein, 1967).

Therefore, the aim of this study was to examine the effects of visual information on neuromuscular activation during bimanual coordination in children with SHCP. If, in line with the kinematic results of Chapter 3, the neuromuscular activity in the mirror and glass condition is similar, then it would indicate that the effect of the mirror is related to a direct coupling between perception and action (i.e., peripheral processes). However, a reduction of neuromuscular activity in the mirror condition would suggest an interaction between central (i.e., efference copy) and perceptual (i.e., afferent signals) processes in children with SHCP during bimanual coordination.

## Methods

### *Participants*

The participants with SHCP were 8 children (mean age 13.9 years, SD = 2.9 years, age range = 9 – 18 years, 6 males and 2 females), who had no history of another neuromuscular disorder. Except for one, all participants indicated that their left arm was less affected than the right arm. The age-matched controls consisted of 12 typically developing (TD) children (mean age 13.2 years, SD = 2.8 years, age range = 9 – 18 years, 9 males and 3 females), all of whom indicated that they were right arm dominant and had no history of a neuromuscular disorders. The individual characteristics of the SHCP and TD children are presented in Table 5.1. Participants were excluded from the study if they had any pain in either of their upper limbs, an uncorrected visual impairment or could not adhere to the required task. The experiment was conducted in accordance with the Declaration of Helsinki. Written informed consent was given by the participants' parents and written informed assent was obtained from all participants. The institutional research ethics committee approved all procedures.

### *Materials and procedure*

A divide (width 0.06 m, depth 0.75 m, height 0.39 m) was securely placed between two custom-built wooden boxes (width 0.59 m, depth 0.17 m, height 0.39 m). The divide was a transparent screen (glass condition), an opaque screen (screen condition) or a mirror (mirror condition). The participant sat on a height-adjustable stool and placed one arm on either side of the divide and angled their head towards the side of their dominant/less impaired arm (Fig. 5.1). In this position, each participant sat with both feet flat on the floor, knees flexed to 90° and elbows flexed to 90°. Participants then gripped in each hand a handle from an arm ergometer (871E, Monark Exercise AB, Vansbro, Sweden). If a participant was unable to grip the handle because of physical impairment, the hand was placed on top of the handle by the experimenter. Each handle was attached to the edge of a wooden disc with a radius of 0.10 m, which spun freely through 360$^{o}$ around a vertical axis. The axes were fixed to a wooden plateau (width 0.60 m, depth 0.46 m, height 0.04 m) and were located 0.31 m apart.

**Table 5.1:** Information on the children with SHCP and their age-matched control(s).

| Participant | Age (Years) | Gender | More Impaired Arm | Severity* AS / GMFCS / WeeFIM | Aetiology | Matched Control Participant (Age / Gender / Arm Dominance) | |
|---|---|---|---|---|---|---|---|
| 1 | 16.3 | F | Left | 1 / 1 / 79 | $O_2$ shortage during birth | 16.7 / M / R | - |
| 2 | 17.1 | M | Right | 2 / 1 / 91 | Cerebral haemorrhage | 16.2 / M / R | - |
| 3 | 9.3 | F | Right | +1 / 1 / 89 | Cerebral haemorrhage | 9.6 / M / R | 9.3 / M / R |
| 4 | 11.0 | M | Right | 1 / 2 / 55 | Meningitis just after birth | 10.0 / F / R | 10.6 / M / R |
| 5 | 12.8 | M | Right | 1 / 1 / 90 | Unknown | 12.4 / F / R | 12.8 / M / R |
| 6 | 13.2 | M | Right | 1 / 1 / 91 | Unknown | 14.0 / F / R | - |
| 7 | 17.4 | M | Right | 1 / 1 / 90 | $O_2$ shortage during birth | 17.2 / M / R | - |
| 8 | 14.3 | M | Right | +1 / 1 / 91 | Cerebral haemorrhage during birth & Meningitis just after birth | 14.8 / M / R | 14.6 / M / R |

*Severity of the child's impairment was assessed by a single experimenter with the modified Ashworth scale (AS), gross motor function classification system (GMFCS) and functional independence measure for children (WeeFIM; motor items only, which had a possible score range of 13 to 91, with a higher score denoting more functional independence of the child).

Before commencing the task, the arms were placed at a start position where they were at the inner most part of each of circle (i.e., nine o'clock for the right arm and three o'clock for the left arm). Participants were asked to perform an inward symmetrical circular bimanual task (i.e. the right arm rotated anti-clockwise and the left arm rotated clockwise irrespective of hand dominance). A bimanual symmetric task was used because it enhanced the 'mirror box' illusion and the homologous muscle groups would be concurrently active, which provided the opportunity to compare the muscle activation of the more impaired with the less impaired arm at the same time. In addition, a circular task involved movements that were not constrained to a single direction and encompassed both anterior-posterior and medial-lateral movements.

Glass Screen Mirror

**Fig. 5.1:** Experimental set up of the mirror box during the glass (left panel), screen (middle panel) and mirror (right panel) condition when the participant's head is positioned towards their dominant arm side to view the bimanual task.

The discs were rotated continuously at a self-selected pace after the start instruction was given and until they were instructed to stop. The participants were also instructed to keep movement time (i.e., movement frequency) constant during the experimental trials. Per condition 3 trials were recorded, which each lasted approximately 15 seconds. Prior to data collection, practice trials were conducted to familiarize the participant with the test setup. In order to keep the participants motivated, they were told that rotating the handles symmetrically resulted in more points being scored, and at the end of the experiment they could trade the points for a small gift.

Superficial EMG was bilaterally recorded from the main muscles around the wrist, elbow and shoulder: flexor digitorum superficialis (FDS), extensor carpi radialis brevis (ECRB), biceps brachii brevis (BBB), tricpes brachii longus (TBL), deltoideus pars anterior (DPA) and deltoideus pars posterior (DPP). A ground electrode was placed over the acromion on the side of the dominant/less impaired arm. Pairs of disposable Ag/AgCl surface EMG electrodes (Blue Sensor Electrodes N, Ambu Inc., Glen Burnie, MD, USA) with a gel-skin contact, active detection area of 15 $mm^2$ for each electrode and a 20 mm centre to centre inter-electrode distance, were placed in parallel with the muscle fibre direction over the muscle bellies after cleaning and gentle abrasion of the skin. The EMG signals were amplified 20 times, high-pass pre-filtered at 10 Hz and AD-converted at 1000 Hz with a 22-bit resolution (Porti-17, Twente Medical Systems, Enschede, The Netherlands, input resistance $>10^{12}\Omega$, CMRR > 90 dB) and stored on a computer. The EMG signals were band-pass filtered with a zero lag $2^{nd}$ order Butterworth filter between 10 and 400 Hz and then full-wave rectified. Finally, the EMG signals were 'smoothed' with a zero-lag $2^{nd}$ order low-pass Butterworth filter at 6 Hz.

Two serially-connected units, each containing three infrared cameras (3020 Optotrak, Northern Digital Inc., Waterloo, Canada), were used to measure the 3D position of relevant anatomical landmarks at 200 Hz. Light emitting diodes were bilaterally attached to the skin with double-sided tape over the dorsal tuberculum of the radius (wrist), lateral epicondyle of the humerus (elbow), greater tubercle of the humerus (shoulder) and trochantor of the femur (hip). The angle of the elbow and shoulder were calculated on either side of the body from the kinematic data. The EMG and motion capture computers were synchronised with a pulse signal.

*Data analysis*

Bilateral EMG recordings were analyzed from the first two cycles[4] of each trial because many children with SHCP could only produce 2 cycles before they changed to a different direction (e.g., outward) or a transition from a symmetric to an asymmetric coordination pattern occurred (i.e., both arms going clockwise or anti-clockwise). Moreover, for some of the children with SHCP, movement time only allowed them to complete 2 cycles within the allocated time of each trial, or the hand slipped of the handle at which point the trial was terminated. Overall, in the TD children group 3 out of 108 trials were excluded from analysis, whereas in the

[4] The first two cycles were derived from the kinematic data from the wrist. Pilot studies showed that participants were able to maintain an anatomical neutral position of the wrist during the movement, which ensured reliable recordings.

children with SHCP group 16 out of 72 trials were excluded from analysis. Movement time was calculated based on the duration of 2 cycles.

Typically, EMG amplitudes are scaled to activation levels recorded either during an isometric maximal voluntary contraction or a specified steady-state sub-maximal contraction. However, this method of normalization is likely to be unreliable in a patient population with neuromuscular dysfunction (Smith et al., 2008; Van Dieën et al., 2003; Perry et al., 2001; Damiano et al., 2000). Therefore, in this study the mean amplitude of the smoothed raw EMG signals (zero-lag 2$^{nd}$ order low-pass Butterworth filter at 6 Hz) was calculated to determine the intensity of the mean neuromuscular activity of each muscle. Furthermore, muscular activity was broken down into phases of active contraction (i.e., eccentric, concentric, and isometric contraction) or relaxation (i.e., inactivity; Fig. 5.2). Determination of the active/inactive threshold for muscle contraction was based on the assumption that a purposeful activation will cause an increase in the EMG signal, particularly in the frequency range of 0 – 160 Hz (Winter, 1979). The active/inactive threshold value (T) was calculated with the following:

$$T = 15 + 1.5R$$

where R is the mean value of the EMG signal above 160 Hz and the constants are derived from Perry et al. (2001). A muscle was considered active if the smoothed raw EMG signal was above the threshold level, otherwise the muscle was considered inactive. Then, the active periods were classified as eccentric, concentric, or isometric for each muscle separately depending on the observed movement and the primary mechanical function of the muscle (see Table 5.2). In the BBB muscle (elbow flexor) for example, periods of elbow flexion were classed as concentric and periods of elbow extension as eccentric. If the muscle was active but there was no change in the joint angle this phase was categorised as isometric. The sum of the duration of all periods per activity category was expressed as a percentage of the total movement time (i.e., 2 cycles). This analysis provided the opportunity to estimate the neuromuscular efficiency during this task around elbow and shoulder and in particular the level of co-contraction (i.e., sum of eccentric and isometric activity).

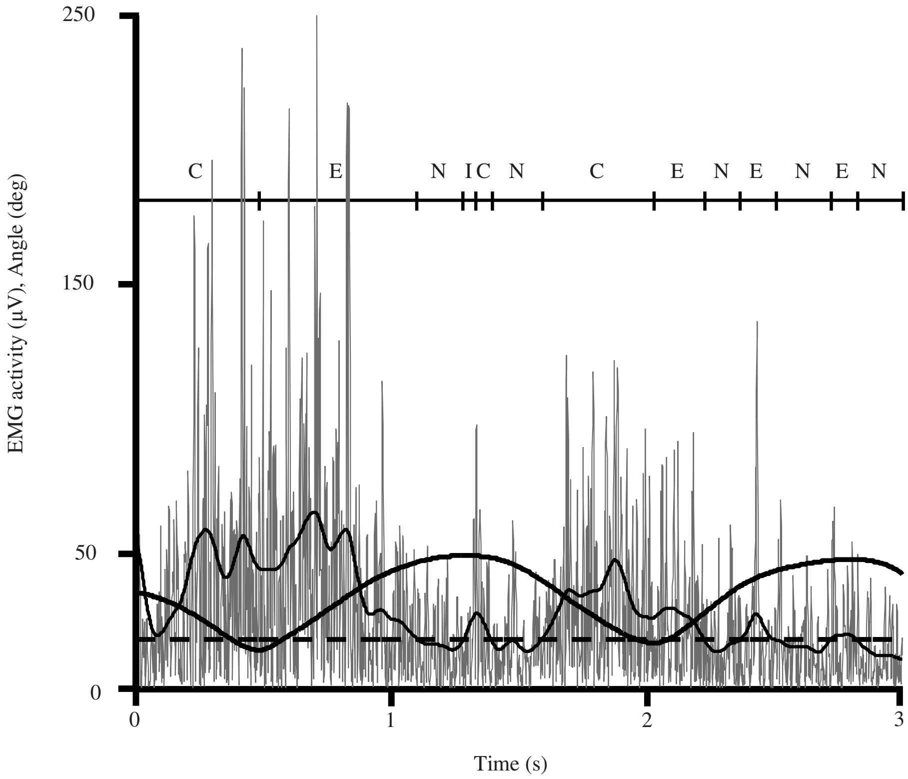



**Fig. 5.2:** Data from a representative trial showing the combination of rectified EMG activity (grey) from the deltoideus pars posterior and shoulder angle (thick) of a TD child's dominant arm. The smoothed EMG (thin) and active/inactive threshold for muscle contraction (dashed) is also depicted. Muscle activation is classed as eccentric (E), concentric (C), isometric (I) and inactivity (N).

**Table 5.2:** Definition of eccentric and concentric activation for the biceps brachii brevis (BBB), triceps brachii longus (TBL), deltoideus pars anterior (DPA), deltoideus pars posterior (DPP) when the angle of the elbow (i.e., angle between forearm and upper arm) and shoulder (i.e., angle between upper arm and trunk) increases and decreases.

| | Elbow angle | |
|---|---|---|
| | Increase | Decrease |
| BBB activity | Eccentric | Concentric |
| TBL activity | Concentric | Eccentric |

| | Shoulder angle | |
|---|---|---|
| | Increase | Decrease |
| DPA activity | Concentric | Eccentric |
| DPP activity | Eccentric | Concentric |

*Statistical analyses*

Group data of movement time were submitted to a mixed ANOVA with one repeated factor, divide (3 levels), and one independent factor, group (2 levels). Furthermore, the neuromuscular intensity data were submitted to a mixed ANOVA with two repeated factors, arm (2 levels) and divide (3 levels), and one independent factor, group (2 levels). Finally, for the muscles around the elbow and shoulder (BBB, TBL, DPA and DPP) a mixed ANOVA with two repeated factors, arm (2 levels) and divide (3 levels), and one independent factor, group (2 levels), was used to compare the relative duration of the four contraction modes (i.e., eccentric, concentric and isometric activation and inactivation) of both groups. Fishers' LSD was used for post hoc analysis. The alpha-level was set at 0.05. Standard error was reported to indicate the true mean variability.

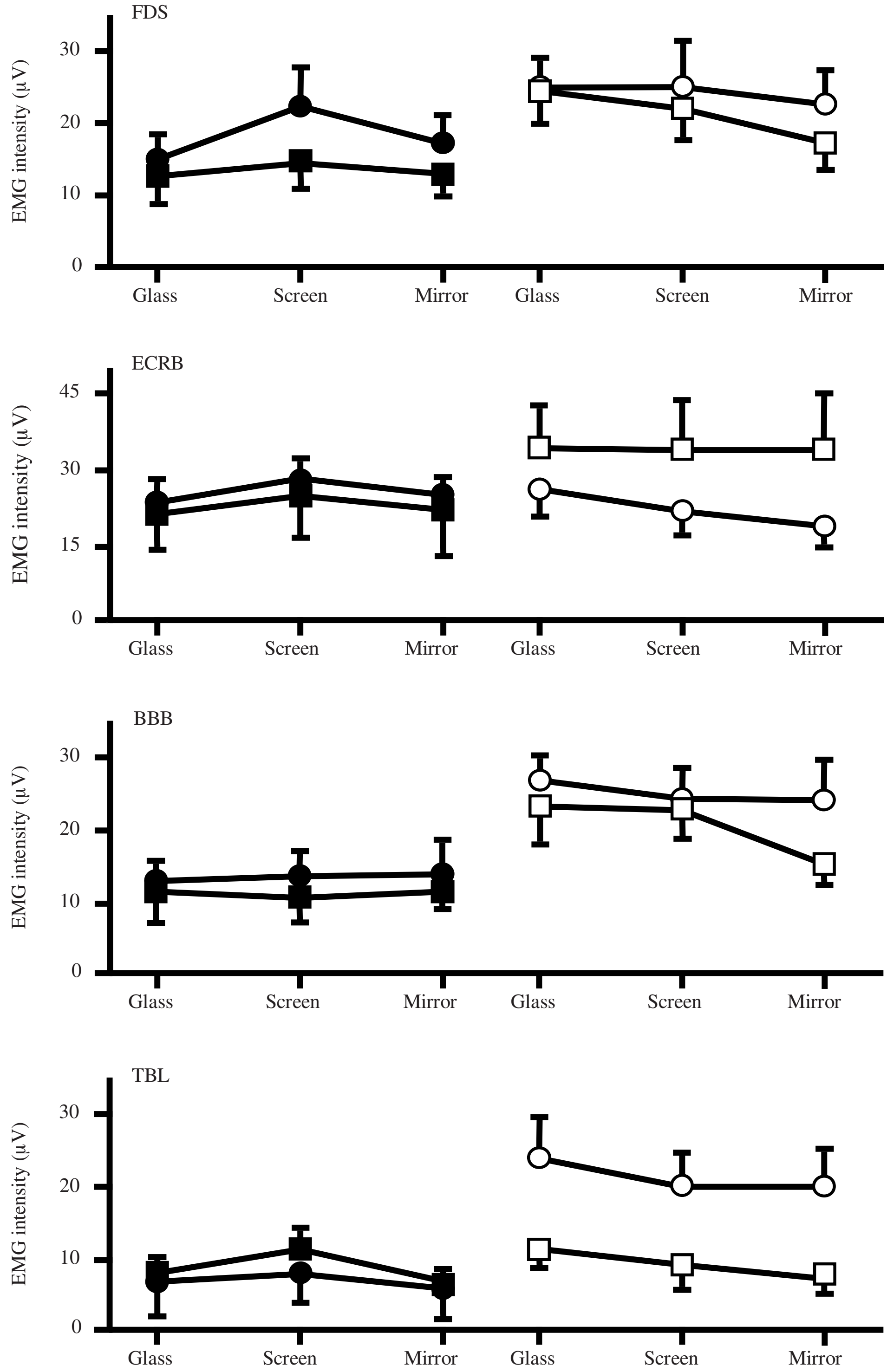
**Results**

*Movement time*

The mean movement time did not differ significantly between the groups (TD = 3.12 ± 0.50 s, range = 1.45 – 7.82 s; SHCP = 3.50 ± 0.61 s, range = 1.43 – 9.66 s) or the divides (glass = 3.15 ± 0.42 s, range = 1.43 – 9.66 s; screen = 3.46 ± 0.48 s, range = 1.43 – 9.32 s; mirror = 3.32 ± 0.35 s, range = 1.45 – 8.07 s; all: $p > 0.49$). There was also no significant group by divide interaction (all: $p > 0.77$), indicating that both groups of children performed the movement at a similar velocity irrespective of the visual manipulations.

*Intensity of neuromuscular activity*

There was a significant main effect of group for the mean neuromuscular activity in the BBB, TBL, DPA and DPP muscles (Fig 5.3; all: $F > 4.99$; $p < 0.05$), which was higher in children with SHCP. Additionally, a significant group by arm interaction was found in the TBL ($F = 4.28$; $p = 0.05$). Post hoc tests did not reveal where this interaction effect occurred (all: $p > 0.09$). However, inspection of the data in Fig. 5.3 suggests a marked difference in EMG intensity between the arms in children with SHCP, whereas in TD children neuromuscular activity of both arms was similar.


FDS
EMG intensity (µV)
30
20
10
0
Glass
Screen
Mirror
Glass
Screen
Mirror
ECRB
EMG intensity (µV)
45
30
15
0
Glass
Screen
Mirror
Glass
Screen
Mirror
BBB
EMG intensity (µV)
30
20
10
0
Glass
Screen
Mirror
Glass
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TBL
EMG intensity (µV)
30
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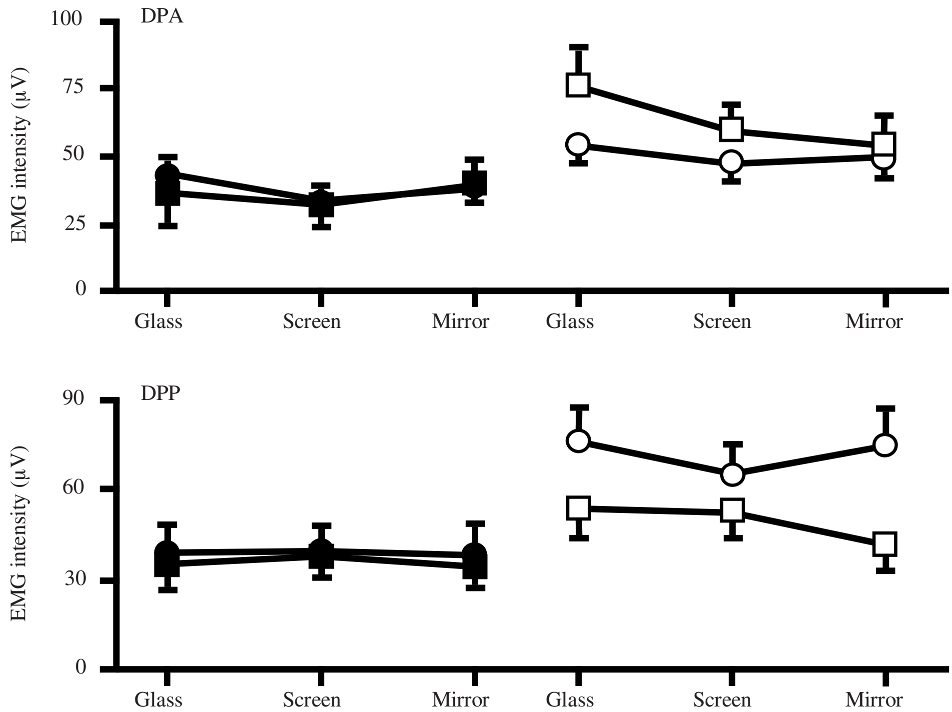


**Fig. 5.3:** EMG intensities for the flexor digitorum superficialis (FDS), extensor carpi radialis brevis (ECRB), biceps brachii brevis (BBB), triceps brachii longus (TBL), deltoideus pars anterior (DPA), deltoideus pars posterior (DPP) in the dominant/less impaired arm (square) and non-dominant/more impaired arm (circle) of the TD children (solid) and children with SHCP (open). Error bars (SE) indicate true mean variability.

Further, there was a significant main effect of divide for the EMG intensity of the DPA muscle (F = 3.39; p = 0.05), which was accompanied by a significant group by arm by divide interaction (F = 3.70; p = 0.05). Post hoc tests revealed that in the more impaired arm of children with SHCP the EMG intensity was unaffected by the visual manipulation. In the less impaired arm, however, the glass condition required higher neuromuscular activity compared to the screen and mirror, which were similar to each other. Additionally, the neuromuscular activity of the less impaired arm in glass and screen condition was significantly higher compared to the more impaired arm. In contrast, the visual manipulation did not affect the EMG intensities of the DPA in TD children; with the exception of a slightly higher intensity in the glass compared to the screen condition for the non-dominant arm (see Fig 5.3).

Finally, a significant arm by divide interaction was found for the neuromuscular activity in the DPP ($F = 3.83$; $p = 0.03$) indicating that in both groups the ipsi– and contralateral arm were affected differently by the visual conditions. Post hoc analyses revealed that the EMG intensity for the dominant/less impaired arm was significantly lower than the non-dominant/more impaired arm (see Fig. 5.3). Additionally, less neuromuscular activity was required in the dominant/less impaired arm during the mirror condition, whilst no divide effect was found for the non-dominant/more impaired arm. Although a significant interaction with the factor group remained absent, this effect was more distinct in the children with SHCP than in TD children (see Fig. 5.3).

*Relative duration of muscle contraction modes*

A breakdown is represented in Table 5.3 for the four muscles separately of the relative contribution of the four contraction modes (eccentric, concentric, isometric and inactive) to the total muscle activity while performing two circles.

*Biceps brachii brevis (BBB)*

The relative duration of eccentric activity in the BBB differed significantly between groups and between arms (both: $F > 8.8$; $p < 0.01$). These effects were accompanied by a significant group by arm ($F = 6.9$; $p = 0.02$) and group by arm by divide interaction ($F = 3.9$; $p = 0.03$; Table 5.3). Post hoc tests revealed that in the children with SHCP the relative contribution of eccentric activity was unaffected by the visual condition in the less impaired arm, whereas in the more impaired arm significantly shorter phases of eccentric contraction were observed in the mirror and screen condition compared to the glass (both: $p < 0.01$). Additionally, the movement of the more impaired arm was achieved with significantly more eccentric BBB contraction compared to the less impaired arm (all: $p < 0.01$). Finally, the relative duration of eccentric activity of the TD children was smaller than for the more impaired arm of children with SHCP (all: $p < 0.01$) and not influenced by the visual manipulation.

BBB muscle activity also consisted of a larger proportion of concentric contraction in children with SHCP ($F = 6.9$; $p = 0.02$), resulting in overall longer periods of activity and shorter periods of relaxation in this group ($F = 10.8$; $p < 0.01$). For the percentage of muscle inactivity a significant main affect of arm ($F = 6.8$; $p =$

0.02) and a significant group by arm by divide interaction (F = 4.4; p = 0.02) were found. In line with the findings for eccentric activity this interaction indicated shorter periods of relaxation in the glass condition compared to the screen and mirror for the more impaired arm of children with SHCP (both: $p < 0.01$). Furthermore, the inactivity of the more impaired arm was significantly shorter compared to the less impaired arm (all: $p < 0.01$). TD children had longer periods of BBB inactivity on the whole compared to the more impaired arm of children with SHCP (all: $p < 0.05$), and the visual manipulations did not have an effect on the relative durations of the contraction modes in this muscle, except for the non-dominant arm during the screen condition where the relaxation period was significantly shorter than the dominant arm in all the conditions (all: $p < 0.05$).

**Table 5.3:** Mean value and SE of percentage muscle activity during the movement task for the biceps brachii brevis (BBB), triceps brachii longus (TBL), deltoideus pars anterior (DPA) and deltoideus pars posterior (DPP) in the dominant/less impaired (dom) arm and the non dominant/more impaired (non – dom) arm of the TD children (TD) and children with SHCP (SHCP). Muscle activity is defined as: eccentric, concentric, isometric and inactive.

| | BBB (% Muscle activity) | | | |
|---|---|---|---|---|
| | Eccentric | Concentric | Isometric | Inactive |
| TD dom | | | | |
| Glass | 6.2 ± (3.0) | 11.0 ± (4.0) | 0.3 ± (0.1) | 82.5 ± (6.5) |
| Screen | 4.6 ± (2.9) | 9.7 ± (3.4) | 0.3 ± (0.2) | 85.4 ± (5.8) |
| Mirror | 6.6 ± (3.5) | 9.8 ± (3.1) | 0.3 ± (0.2) | 83.3 ± (6.4) |
| TD non - dom | | | | |
| Glass | 6.4 ± (4.1) | 13.4 ± (3.4) | 0.2 ± (0.8) | 80.0 ± (7.2) |
| Screen | 7.7 ± (4.9) | 16.8 ± (4.2) | 0.6 ± (1.0) | 74.9 ± (8.7) |
| Mirror | 6.4 ± (4.6) | 13.6 ± (3.6) | 0.5 ± (0.7) | 79.5 ± (8.0) |
| SHCP dom | | | | |
| Glass | 14.7 ± (3.6) | 19.3 ± (4.9) | 0.5 ± (0.2) | 65.5 ± (8.0) |
| Screen | 16.8 ± (3.5) | 19.6 ± (4.2) | 0.8 ± (0.2) | 62.8 ± (7.1) |
| Mirror | 12.3 ± (4.2) | 17.1 ± (3.8) | 1.0 ± (0.3) | 69.6 ± (7.8) |
| SHCP non - dom | | | | |
| Glass | 37.6 ± (5.0) | 29.3 ± (4.2) | 2.5 ± (1.0) | 30.6 ± (8.9) |
| Screen | 28.2 ± (6.1) | 25.6 ± (5.1) | 2.8 ± (1.2) | 43.4 ± (10.6) |
| Mirror | 27.4 ± (5.6) | 25.0 ± (4.4) | 2.3 ± (0.9) | 45.3 ± (9.8) |

| TBL (% Muscle activity) | | | | |
|---|---|---|---|---|
| | Eccentric | Concentric | Isometric | Inactive |
| TD dom | | | | |
| Glass | 3.7 ± (2.3) | 6.0 ± (2.8) | 0.1 ± (0.1) | 90.2 ± (5.0) |
| Screen | 9.4 ± (3.5) | 13.4 ± (4.2) | 0.7 ± (0.4) | 76.5 ± (7.6) |
| Mirror | 2.6 ± (1.9) | 4.2 ± (2.1) | 0.1 ± (0.1) | 93.1 ± (3.7) |
| TD non - dom | | | | |
| Glass | 1.9 ± (2.7) | 3.6 ± (3.5) | 0.3 ± (0.7) | 94.2 ± (6.5) |
| Screen | 4.5 ± (3.2) | 5.1 ± (4.3) | 0.1 ± (1.0) | 90.3 ± (7.9) |
| Mirror | 2.3 ± (2.7) | 1.6 ± (2.9) | 0.1 ± (0.7) | 96.0 ± (6.0) |
| SHCP dom | | | | |
| Glass | 9.6 ± (2.9) | 10.6 ± (3.5) | 0.3 ± (0.1) | 79.5 ± (6.1) |
| Screen | 4.4 ± (4.3) | 7.2 ± (5.1) | 0.1 ± (0.4) | 88.3 ± (9.3) |
| Mirror | 4.1 ± (2.3) | 2.1 ± (2.6) | 0.1 ± (0.1) | 93.7 ± (4.5) |
| SHCP non - dom | | | | |
| Glass | 14.2 ± (3.3) | 16.3 ± (4.3) | 1.7 ± (0.9) | 67.8 ± (8.0) |
| Screen | 14.0 ± (3.9) | 17.0 ± (5.2) | 2.4 ± (1.2) | 66.6 ± (9.7) |
| Mirror | 14.0 ± (3.3) | 9.7 ± (3.5) | 1.7 ± (0.8) | 74.6 ± (7.4) |

| DPA (% Muscle activity) | | | | |
|---|---|---|---|---|
| | Eccentric | Concentric | Isometric | Inactive |
| TD dom | | | | |
| Glass | 27.3 ± (4.4) | 37.9 ± (3.5) | 2.4 ± (1.0) | 32.4 ± (7.2) |
| Screen | 26.2 ± (4.2) | 32.1 ± (3.8) | 1.2 ± (0.4) | 40.5 ± (6.8) |
| Mirror | 27.8 ± (4.6) | 36.5 ± (3.4) | 1.1 ± (0.3) | 34.6 ± (7.6) |
| TD non - dom | | | | |
| Glass | 30.9 ± (3.2) | 43.1 ± (2.3) | 1.1 ± (0.8) | 24.9 ± (3.8) |
| Screen | 28.6 ± (3.8) | 35.5 ± (3.5) | 1.0 ± (0.5) | 34.9 ± (5.9) |
| Mirror | 29.2 ± (4.2) | 37.1 ± (1.9) | 1.2 ± (0.4) | 32.5 ± (5.5) |
| SHCP dom | | | | |
| Glass | 35.9 ± (5.4) | 40.9 ± (4.3) | 1.2 ± (1.2) | 22.0 ± (8.9) |
| Screen | 42.9 ± (5.2) | 45.5 ± (4.6) | 1.6 ± (0.5) | 10.0 ± (8.4) |
| Mirror | 34.9 ± (5.7) | 41.1 ± (4.2) | 1.7 ± (0.4) | 22.3 ± (9.3) |
| SHCP non - dom | | | | |
| Glass | 40.5 ± (3.9) | 44.7 ± (2.8) | 2.9 ± (0.9) | 11.9 ± (4.7) |
| Screen | 35.1 ± (4.6) | 42.4 ± (4.3) | 2.2 ± (0.6) | 20.3 ± (7.3) |
| Mirror | 36.0 ± (5.1) | 44.2 ± (2.4) | 1.5 ± (0.5) | 18.3 ± (6.7) |

| | DPP (% Muscle activity) | | | |
|---|---|---|---|---|
| | Eccentric | Concentric | Isometric | Inactive |
| TD dom | | | | |
| Glass | 24.1 ± (4.8) | 32.5 ± (4.3) | 1.7 ± (0.7) | 41.7 ± (8.5) |
| Screen | 25.2 ± (4.5) | 37.3 ± (3.5) | 1.3 ± (0.4) | 36.2 ± (7.2) |
| Mirror | 26.5 ± (4.7) | 34.0 ± (4.3) | 1.0 ± (0.4) | 38.5 ± (8.4) |
| TD non - dom | | | | |
| Glass | 28.5 ± (4.4) | 38.0 ± (3.4) | 1.0 ± (0.8) | 32.5 ± (6.8) |
| Screen | 27.4 ± (4.5) | 39.7 ± (3.1) | 1.0 ± (0.5) | 31.9 ± (6.2) |
| Mirror | 27.0 ± (3.5) | 39.3 ± (3.5) | 1.1 ± (0.3) | 32.6 ± (6.6) |
| SHCP dom | | | | |
| Glass | 37.4 ± (5.8) | 34.6 ± (5.3) | 1.3 ± (0.9) | 26.7 ± (10.4) |
| Screen | 36.2 ± (5.6) | 39.6 ± (4.3) | 1.5 ± (0.5) | 22.7 ± (8.9) |
| Mirror | 33.2 ± (5.8) | 34.3 ± (5.3) | 1.9 ± (0.5) | 30.6 ± (10.3) |
| SHCP non - dom | | | | |
| Glass | 43.2 ± (5.3) | 45.7 ± (4.2) | 2.8 ± (0.9) | 8.3 ± (8.4) |
| Screen | 38.2 ± (5.5) | 43.6 ± (3.8) | 2.3 ± (0.6) | 15.9 ± (7.6) |
| Mirror | 40.3 ± (4.3) | 45.4 ± (4.2) | 1.6 ± (0.4) | 12.7 ± (8.1) |

*Triceps brachii longus (TBL)*

There was a significant group by arm interaction for the TBL eccentric activity ($F = 5.2$; $p = 0.04$). Post hoc tests were unable to locate the source of this interaction (all: $p > 0.14$), but close inspection of the values in Table 5.3 suggests a considerable arm difference in children with SHCP that is absent in TD children. In SHCP children, TBL activity in the more impaired arm consists of relatively more eccentric activity than in the less impaired arm. The percentage of eccentric activity of this more impaired arm was also larger than in TD children.

A similar picture was observed for the concentric activity, with again a significant group by arm interaction ($F = 4.6$; $p = 0.05$). Although the post hoc analysis yielded no statistically significant differences (all: $p > 0.22$), the percentages of concentric activity in the more impaired arm of children with SHCP again appear higher than in the less impaired arm and both arms of the TD children. Furthermore, a significant effect of divide was found for this variable ($F = 5.3$; $p = 0.01$). TBL activity in both population groups consisted of shorter phases of concentric contraction in the mirror condition compared to the screen condition ($p = 0.03$), whereas TBL concentric activity in the glass condition did not differ from both other conditions.

Although the percentage of isometric activity was considerably small (0.1 – 2.4%) because of the dynamical nature of the task, the statistical analysis indicated a significant group by arm by divide interaction for the TBL isometric activity ($F = 4.1$; $p = 0.05$). Essentially, this interaction revealed a significantly longer period of isometric activity in the more impaired arm compared to the less impaired arm of children with SHCP (all: $p < 0.01$), while no difference was found in the TD group. Furthermore, the TBL isometric activity of the more impaired arm was also significantly longer than in TD children. This was especially apparent in the screen condition (all: $p < 0.05$). The visual manipulations did not affect the relative durations of the isometric contractions in the arms of the TD children, except for the dominant arm during the screen condition where the activation was significantly longer compared to the other observations (all: $p < 0.05$).

Finally, a significant group by arm interaction was found for the TBL inactivity ($F = 5.2$; $p = 0.04$). Although the post hoc tests were unable to detect the location of the interaction (all: $p > 0.16$), the findings are in line with the results for eccentric and concentric activity, with shorter periods of relaxation in the more impaired arm of children with SHCP compared to less impaired arm and both arms of TD children.

*Deltoideus pars anterior (DPA)*

No differences were found for the proportions of eccentric, concentric, and isometric contraction in the total activity of this muscle. However, a significant group effect for the percentage of inactivity ($F = 4.5$; $p = 0.05$) indicated that the DPA muscles of children with SHCP were relatively more active throughout the movement compared to TD children.

*Deltoideus pars posterior (DPP)*

The relative portion of DPP eccentric activity was significantly larger in children with SHCP ($F = 4.8$; $p = 0.04$). Furthermore, there was a significant main effect of arm for the DPP concentric activity ($F = 5.5$; $p = 0.03$). This effect indicated that the movement of the non-dominant/more impaired arm required relatively more DPP concentric contraction than in the dominant/less impaired arm. Finally, a significant divide by arm interaction was found for the DPP inactivity ($F = 3.6$; $p = 0.04$) Post hoc tests revealed that the dominant/less impaired arm was less active compared to the non-dominant/more impaired arm (all: $p < 0.05$). Additionally, longer periods of relaxation in the dominant/less impaired arm during the glass and mirror compared to the screen condition (both: $p < 0.05$). In the non-dominant/less impaired arm no significant effect of the visual manipulation was observed.

**Discussion**

This study examined the neuromuscular activity of the arm muscles in children with and without SHCP when performing a symmetrical circular bimanual task under different visual conditions. It was found that children with SHCP had higher mean EMG intensities in the muscles around the elbow and shoulders compared to TD children. Markedly, the levels of mean neuromuscular activation of the more and the less impaired arm were similar, except for the TBL where the EMG intensity of the more impaired arm was higher. These results show that although children with SHCP require higher mean neuromuscular activity in comparison with TD children to perform the same task, the characteristic asymmetry between body-sides overtly found in SHCP was absent at a neuromuscular level. In the mirror condition, the children with SHCP had significantly lower DPP EMG intensities in the less impaired arm compared to the glass and screen condition. Furthermore, the EMG intensity of the DPA in the less impaired arm of children with SHCP was significantly higher when the glass was placed between their arms compared to when an opaque screen or a mirror was in place. In conjunction, longer eccentric activation and shorter relaxation periods in the elbow flexor (i.e., BBB) of their more impaired arm were found in the glass condition compared to the opaque screen and mirror conditions. In the more impaired arm the phases of concentric and isometric activation of the TBL and the activity of the DPP were significantly longer in the screen condition compared to the glass and mirror condition. Finally, the manipulation of visual information did not affect the neuromuscular activation in TD children to the same extent as children with SHCP. However, a slightly higher EMG intensity was found in the DPA of the non-dominant arm during the glass compared to the screen condition. Additionally, the period of BBB inactivity in the non-dominant arm was shorter and the period of TBL isometric activity in the dominant arm was longer during the screen condition compared to the other observations.

These results show that the neuromuscular activity of children with SHCP reduced when veridical visual feedback was absent (i.e., screen and mirror condition) which is in accordance with previous studies that demonstrated that the manipulation of visual information can override neuromuscular activation (Mechsner et al., 2001; Tomatsu & Ohtsuki, 2005). The acute effects of the mirror found in the current study support the hypothesis that a decrease in the discrepancy between the afferent visual feedback and efference copy contributes to the impaired motor behaviour in children with SHCP when performing a symmetrical bimanual task (Ramachandran, 2005). Additionally, this hypothesis may also offer an explanation for the lower neuromuscular activity in the screen compared to the glass condition. In the presence of both visual and proprioceptive feedback, the relative contribution of vision has been shown to outweigh proprioception (Mechsner et al., 2001). When visual feedback is absent, however, the contribution of proprioception is increased so that the interlimb coordination is prevailed. This reweighing of afferent signals is observed in children as young as 5 years old (Chapter 2). However, the proprioceptive information in children with SHCP is to some extent distorted (Van Der Weel et al., 1995), which makes proprioceptive information unable to detect a discrepancy with the efference copy. Instead of amplifying the motor outflow, the current results suggest that the inaccurate proprioceptive information apparently ‘confirms’ that the efferent signals had been obeyed, which damped the motor outflow. However, other findings indicate that additional factors may contribute to the generation of muscle activity. For instance, the duration of concentric contraction of the TBL and the mean neuromuscular activity of the DPP in the more impaired arm were respectively shorter or lower in the glass and mirror conditions compared to the screen condition. These observations show that veridical visual information does not always lead to higher EMG values and less relaxation and that other mechanisms also affected the movement. In the screen condition children with SHCP were faced with the problem that the more impaired arm needed to maintain in-phase with the less impaired arm, in the absence of visual feedback of the more impaired arm. In order to perform the required task, children may choose to increase the duration of contraction in certain muscles of the more impaired arm and thereby increasing joint stiffness (Feltham et al., 2006). This could be a way to increase joint impedance, which, in turn, enhance movement accuracy (Van Galen & Schomaker, 1992; Van Galen & De Jong, 1995; Selen et al., 2006a; 2006b) and as a consequence may ease the control of the movement. However, additional research is needed to further clarify the specific findings of the effects of the glass and screen conditions.

In Chapter 3, which examined the contribution of visual feedback to the kinematical aspects of interlimb coordination, a significant decrease in the temporal movement variability between the arms in the mirror and glass conditions compared to the opaque screen condition was found. These results indicate that children with SHCP maintained a stable movement coupling between their arms when visual feedback was available of the more impaired arm or replaced by a mirror reflection of the less impaired arm. In the current study the neuromuscular activity was lower in certain muscles during the mirror condition along with either the glass or the screen conditions. However, the important point to note is that in the mirror condition the neuromuscular activity was never the highest compared to the other visual conditions. Therefore, the combined results of both the kinematic and neuromuscular aspects of the bimanual circle drawing suggest that placing a mirror between the arms of children with SHCP, to replace the visual information of the more impaired arm with the mirror reflection of the less impaired arm, seems to improve their motor behaviour more than any other condition.

Furthermore, the current study found that children with SHCP had higher mean neuromuscular activity compared to TD children when performing a symmetrical circular bimanual task. The higher neuromuscular intensities found in the arm muscles of children with SHCP compared to TD children are consistent with previous studies that investigated the EMG activity in the leg muscles (Wakeling et al., 2007; Perry et al., 2001; Damiano et al., 2000; Ikeda et al., 1998). Interestingly, as reported in Chapter 4, the EMG intensities in the more and the less impaired arm of children with SHCP were similar. This supports the notion that although SHCP is characterised by a strong asymmetry between body-sides, the unilateral brain damage results in changes to the motor control of both sides of the body (Yarosh et al., 2004; Wiley & Damiano, 1998). Yarosh et al. (2004) hypothesized that, at a cortical level, unilateral damage alters the intact brain hemisphere’s excitability because it takes over certain functions from the damaged brain hemisphere. Execution of a movement with the more impaired arm is thought to be generated by a motor command originating in the intact brain hemisphere that is sent to the non-intact brain hemisphere via interhemispheric connections and subsequently relayed towards the more impaired arm. However, Volman et al. (2002) proposed that the motor commands from the intact hemisphere can be sent through ipsilateral pathways to the more impaired arm, without being transmitted to the other brain hemisphere. Future research with transcranial magnetic stimulation and functional magnetic resonance imaging of children with SHCP might disclose further evidence to support one of these notions.

The more detailed analysis of the relative distribution of the muscle contraction modes showed distinct differences between the more and the less impaired arm. More specifically, children with SHCP had longer phases of eccentric and concentric activation and, consequently, shorter phases of relaxation in the muscles around the elbow of the more impaired arm. This could be an indication of the difference in spasticity between the body-sides, which is a direct consequence of the disorder (Steenbergen et al., 2008). Secondary to the neurological damage, the increased period of muscle activation might be a result of muscle weakness, as was previously reported with respect to leg muscles of children with spasticity (Wiley & Damiano, 1998). Alternatively, although not mutually exclusive, the longer durations of activity, including co-activation (eccentric activity), might be a reflection of a joint stabilisation strategy that allows more rapid responses to (unexpected) perturbations (Damiano et al., 2000). Whilst this strategy may enable children with SHCP to meet the constraints of the task and execute the bimanual circular movement, the co-activation has a negative effect on the movement efficiency, with higher energy expenditure leading to quicker onset of muscular fatigue.

The current findings offer a better insight into the contribution of visual information to the neuromuscular activity that act on bimanual coordination in children with SHCP. However, it should be acknowledged that our study could only shed a light on the first 2 cycles of the circular movement. It may therefore be argued that our conclusions merely apply to the initiation of a movement (i.e., first 2 cycles) rather than to a 'steady state' cyclical movement (i.e., 5 cycles or more). More cycles would have been optimal to examine the interlimb coordination and neuromuscular activity during this task, but the motor impairment of the children with SHCP did not allow most (n = 6) of the participants to sustain or even attain a 'steady state'. These observations are also important to consider when constructing exercises for the 'mirror box' in a clinical setting.

In conclusion, this study showed that children with SHCP required higher amounts of neuromuscular activity than TD children during bimanual circle drawing, but that the EMG intensities were similar for the more and less impaired arm. Moreover, during the movement children with SHCP tended to activate their elbow muscles in the more impaired arm over longer periods (both in concentric and eccentric contraction) indicating shorter phases of relaxation. Furthermore, EMG intensities in the shoulder muscles of children with SHCP were lower when the mirror was in place compared to the other visual manipulations, especially the glass condition. Similar attenuating effects of the mirror were found for the relative durations of eccentric and concentric activity in the elbow muscles. These results indicate that a discrepancy between the actual visual feedback and internal efference copy may contribute to the motor difficulties in children with SHCP, which may be reduced by removing or replacing the visual information of the more impaired arm with a mirror reflection of the less impaired arm. Previous research found a significantly lower temporal variability between the arms when children with SHCP had the mirror between their arms compared to a condition without visual information from the impaired arm. In combination with these kinematic results, the current findings suggest that replacing the visual information of the more impaired arm with the mirror reflection of the less impaired arm might improve motor behaviour in children with SHCP. Forthcoming experiments with more prolonged training protocols are warranted to determine whether the 'mirror box' has any long-term benefits on functional motor behaviour, which transfer positively to other daily life activities.

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# CHAPTER 6

## Epilogue

This thesis investigated bimanual coordination and neuromuscular activation in children with and without spastic hemiparetic cerebral palsy (SHCP) under conditions of visual feedback created by placing a glass screen, opaque screen or a mirror ('mirror box') between the arms. Using this arrangement, visual information could be seen from both arms (glass condition), from one arm only (opaque screen condition), or from one arm and a mirror reflection ('mirror box' condition) that superimposes the arm behind the mirror. When both arms are moved simultaneously in the latter condition, a strong visual illusion is created, which gives rise to a visual perception of a zero lag, symmetric movement between the two arms. In individuals with a strong asymmetry between body-sides (i.e., adults with hemiparesis after stroke or children with SHCP) viewing the less impaired arm and its reflection in the mirror gives an interesting possibility to see two less impaired arms. Previous research has shown that the 'mirror box' can exert an influence on interlimb movement in typically developed adults (Franz & Packman, 2004) and adults with hemiparesis following a stroke (Stevens & Stoykov, 2004, 2003; Altshuler et al., 1999). Children with SHCP have comparable overt asymmetries between the body-sides to adults with hemiparesis and their interlimb movement may be similarly influenced when they perform bimanual movements in the 'mirror box'. However, children with SHCP may have developed different motor strategies and/or behaviour because they never effectively learned to use their more impaired arm (Charles & Gordon, 2006; Latash & Anson, 1996). Therefore, the studies in this thesis needed to explore the effect of the 'mirror box' on children with SHCP.

To facilitate the understanding of the findings in children with SHCP with regard to bimanual coordination, a detailed insight into the development of kinematical and neuromuscular aspects in typically developing (TD) children is required, in addition to the contribution of visual information towards interlimb coupling. In previous studies, temporal variability of bimanual coordination decreased during development, which was particularly significant around the age of 7 years (Robertson, 2001; Fitzpatrick et al., 1996). The increased stability of interlimb coupling with age might be directly associated with improvements in the neuromuscular synergistic activity around the joints (Grosset et al., 2008; Lambertz et al., 2003). However, it has also been suggested that the divergence between younger and older children can be attributed to a difference in visual attention towards the bimanual task (Pellegrini et al., 2004; Anslin & Cuiffreda, 1983). In order to distinguish between the two speculated factors, the contribution of visual information to interlimb coordination and neuromuscular activation across development was investigated during a symmetrical bimanual movement.

The main findings from this thesis can be summarized as follows:

1. The younger TD children (aged 5 – 10 years) were able to maintain a similar mean temporal coordination pattern (i.e., mean CRP and movement time) compared to the older age group (12 – 18 years). However, younger children had greater interlimb temporal variability and higher levels of neuromuscular activity compared to the older children. The reduction in interlimb movement variability and neuromuscular activity during development when performing a bimanual task might indicate an association between these factors (Chapter 2).
2. The movement coordination between the arms and neuromuscular activation in the TD children remained constant when visual information was manipulated across development. These results indicate that the manipulation of visual information did not affect the bimanual movement coordination or the mean neuromuscular activation of the TD children. It suggests that the contribution of visual information towards bimanual movement might have been interchangeable with proprioceptive feedback to maintain interlimb movement variability between the conditions (Chapter 2).
3. Children with SHCP were able to maintain a similar mean temporal coordination pattern, but exhibited greater interlimb temporal variability compared to TD age-matched controls (Chapter 3). Furthermore, when visual information was manipulated, the interlimb movement variability in children with SHCP was significantly greater in the screen condition compared to the glass and mirror condition, which were similar to each other. These findings suggest children with SHCP had difficulties maintaining a stable interlimb coupling when visual information of the impaired arm was absent. Furthermore, when children with SHCP could see a mirror reflection of their less impaired arm, it resulted in levels of movement variability similar to that when performing in the glass condition.
4. TD children had lower mean neuromuscular intensities during a bimanual symmetrical circular movement compared to children with SHCP (Chapter 4). However, in children with SHCP the mean neuromuscular intensities of the less and more impaired arm were similar. Furthermore, the motor behaviour of the children with SHCP was characterised by longer phases of eccentric and concentric activity,

especially in the more impaired arm, which indicates that more co-activation was required to perform the bimanual task. The electromyography (EMG) signals yielded a higher mean power frequency in all the muscles of the more impaired arm in conjunction with the wrist and elbow flexors of the less impaired arm. These results reflect the activation of relatively more type II fibres in children with SHCP during the movement compared to TD children. Furthermore, this suggests that the effect of SHCP on the muscles involved structural changes in addition to differences in muscle activation.

5. Finally, the neuromuscular activity of children with SHCP seemed to reduce when veridical visual feedback was absent (i.e., in the screen and mirror condition), which confirms that the manipulation of visual information can influence motor behaviour during bimanual coordination (Chapter 5). Interestingly, the acute effects of the mirror found in this study supported the hypothesis that enhanced reconciliation between visually perceived movement (afferent visual feedback) and intended movement (efference copy) reduces impaired motor behaviour in children with SHCP when performing a symmetrical bimanual task.

**Underlying mechanisms**

The object of this thesis was to further enhance our understanding of bimanual coordination in children with and without SHCP and gain insight into the contribution of visual information towards interlimb coupling. The bimanual movement coordination and mean neuromuscular activation of the TD children were not affected across development when visual information was manipulated. This suggests that the contribution of visual information might have been interchangeable with proprioceptive feedback to maintain a constant interlimb movement variability and neuromuscular activation between the conditions. Furthermore, younger children exhibited more temporal movement variability between the limbs and higher levels of neuromuscular activity compared to older children during a symmetrical bimanual movement. The decrease in interlimb coordination variability suggests that during development more stable patterns of coupling (i.e., tighter temporal coupling) between the arms are being established and enhanced. In addition, the reduced EMG intensity in the older children implies a more efficient activation of the involved muscles during the task (i.e., less neuromuscular activation for the same task) compared to the younger children. Although it is not possible to establish a direct cause and effect relationship between the interlimb movement variability and neuromuscular activity, it may indicate an association between these factors during development when performing a bimanual movement.

The movement features of the more impaired body-side of children with SHCP are often characterised as slow and jerky with higher levels of co-activation (Steenbergen et al., 2008; Wakeling et al., 2007; Perry et al., 2001; Ikeda et al., 1998). However, the observations of higher levels of co-activation are based on measurements obtained from the lower limbs. Before the neuromuscular activation in children with SHCP could be examined under conditions of visual feedback, a base rate recording was conducted of the neuromuscular activity and frequency content of the EMG signals from the arm muscles in children with SHCP and TD children. The results showed that in accordance with the measurements taken from the lower limb, children with SHCP generally had higher mean EMG intensities compared to TD children. Interestingly, intensities of mean neuromuscular activity in the more and less impaired arm in children with SHCP were similar, which suggests bilateral coupling between the arms. The performance of bimanual tasks involves an interplay of neurological structures at different levels within the central nervous system, which are difficult to address in isolation given the complexity of the interaction and the difficulty to measure and visualize activity at specific levels. However, with regard to the cortical level it was hypothesized by Yarosh et al. (2004) that unilateral damage alters the intact brain hemisphere's excitability because it takes over certain functions from the damaged brain hemisphere. Execution of a movement with the more impaired arm is thought to be generated by a motor command originating in the intact brain hemisphere that is sent to the non-intact brain hemisphere via interhemispheric connections and subsequently relayed towards the more impaired arm.

A more comprehensive insight into the sensorimotor reorganisation in individuals with congentital hemiparesis has been conducted in a series of experiments by Staudt and co-workers (Staudt et al., 2000; Staudt et al., 2002; Staudt et al., 2004). The functional integrity of crossed cortico-spinal projections in the affected brain hemisphere, as well as the presence of any ipsilateral projections to the more impaired arm, was examined by transcranial magnetic stimulation (TMS). In addition, cortical activation during simple voluntary arm movements was studied by functional magnetic resonance imaging (fMRI). It was found that motor evoked potentials (MEPs) in the more impaired arm were still elicitable by TMS of the affected brain hemisphere in individuals with a small lesion and only mild arm movement impairments. This indicates that the primary motor representation of the paretic arm had not changed. Nevertheless, fMRI demonstrated an increased cortical activation in the unaffected brain hemisphere. However, TMS of these activated areas did not elicit motor responses in the more impaired arm, confirming that they acted as non-primary motor areas. This type of ipsilateral cortical activation has been attributed, at least in part, to the increased functional demand even simple arm movements pose on the sensorimotor system after partial structural damage (Cramer & Bastings, 2000), since similar ipsilateral cortical activation patterns have been observed in healthy subjects when performing complex unimanual movements (Wexler et al., 1997; Catalan et al., 1998). Therefore, the patterns of ipsilateral recruitment identified in the group of individuals with a small unilateral brain lesion and mild arm movement impairments are apparently not specific to the corticospinal reorganisation after brain lesions. Rather, it seems that this type of ipsilateral recruitment is a common mechanism in response to increased functional demands during unimanual movements also observed in healthy individuals (Staudt et al., 2002).

In contrast to the previous findings, it was found by Staudt and colleagues (2002) that when TMS was applied to the affected brain hemisphere in individuals with large lesions and more severe hand motor impairment, MEPs were absent in the more impaired arm. However, motor responses in the more impaired arm were elicitable by TMS of the unaffected brain hemisphere, demonstrating the presence of ipsilateral motor projections and indicating that the primary motor representation of the more impaired arm was re-located to the unaffected brain hemisphere. Apparently, large unilateral brain lesions do disrupt the corticospinal tract and the subsequent reorganisation can induce the activation of ipsilateral pathways (Staudt et al., 2002). These different TMS findings were correlated with the severity of structural damage to arm motor projections of the pyramidal tract, as quantified on MRI reconstructions (Staudt et al., 2000). Interestingly, the efficacy of ipsilateral corticospinal tract reorganisation decreased in individuals who suffered congenital unilateral brain damage after the second trimester of the pregnancy (Staudt et al., 2004). The results from the work by Staudt and his colleagues suggest that in future studies, which investigate the effects of a more prolonged training protocol with the ‘mirror box’ on the bimanual coordination in children with SHCP more clinical information and characteristics about the unilateral brain legion is required to understand the underlying mechanisms involved. Furthermore, this insight will be paramount to develop the ‘mirror box’ as a mainstream therapy within a clinical setting.

Subsequent analysis showed that with regard to the nature of muscular activity children with SHCP had longer phases of eccentric and concentric activity and, consequently, shorter phases of muscular inactivity in the muscles around the elbow. This was predominantly prevalent in the muscular activation pattern in the more impaired arm of children with SHCP. This could be an indication of the difference in spasticity between the body-sides, which is a direct consequence of the neurological damage. Secondary to the condition, the increased period of muscle activation might be a result of muscle weakness. Alternatively, but not mutually exclusive, the increased neuromuscular intensities in the elbow flexors and extensors and concomitant rise in co-activation may also be the result of a need to stabilize joints. Higher levels of co-activation increases joint stability (Feltham et al., 2006) and joint impedance, which, in turn, enhance movement accuracy (Van Galen & Schomaker, 1992; Van Galen & De Jong, 1995; Selen et al., 2006a; 2006b). This allows the motor system to respond more quickly to (unexpected) perturbations, which are likely to be present in children with SHCP due to irregular and jerky movements of the more impaired arm (Damiano et al., 2000) or unstable posture (Coluccini et al., 2007). Therefore, the excessive co-activation in children with SHCP is probably the result of a trade-off between executing the bimanual circular movement and a useful compensatory strategy (Selen et al., 2005; Van Dieën et al., 2003) by increasing movement accuracy to reduce any (unexpected) inappropriate movements of the more affected arm influenced primarily by damage to the central nervous system. However, the (excessive) co-activation is likely to increase energy expenditure, which, in turn, may result in a quicker onset of muscular fatigue.

Next to the differences with regard to neuromuscular activation, the mean power frequencies in the EMG signals of children with SHCP were higher compared to the TD children, especially in the more impaired arm. The high-frequency components of the EMG spectrum have been suggested to be a reflection of the high-frequency content of action potentials generated by the fast fibre types, whereas the slow fibre types generate low-frequency action potentials. Therefore, the higher mean power frequency values for the muscles in the more impaired arm of children with SHCP might indicate that during the bimanual movement relatively more fast-twitch muscle fibres (i.e., type II muscle fibres) were activated in children with SHCP compared to TD children. This phenomenon may have been caused by systematic atrophy of type I muscle fibres in the more impaired arm. This supports the notion that spasticity is not only manifested at the functional level but also alters muscle structure through the re-distribution of muscle fibre types. Alternatively, these higher mean power frequency values might indicate that larger motor units, which generally contain fast fibre types (i.e., size principle), were active during the execution of this bimanual task. This is reflected in the higher neuromuscular intensities. However, given the different pattern of EMG intensity and mean power frequency in relation to the less and more impaired arm, it should be noted that higher mean power frequencies are not just a linear function of higher EMG intensity.

For instance, in the wrist and elbow flexors (FDS and BBB) there was no difference between the more and less impaired arm in children with SHCP for the EMG intensities and the mean power frequencies. Here the larger mean power frequencies compared to the TD children might be a reflection of more motor units being activated, because a higher mean neuromuscular intensity was also observed (i.e., size principle). This suggests that unilateral brain damage results in changes to the motor control of not only the contralateral body-side but also the ipsilateral side (Yarosh et al., 2004; Wiley & Damiano, 1998) and implies that the arms are more bilaterally coupled with each other than in a typical population. However, in the other muscles an asymmetrical pattern between the arms was found for the mean power frequencies (i.e., the mean power frequency was greater in the more impaired arm than in the less impaired arm), while the EMG intensities between the arms were similar, except for TBL. This suggests that the recruitment of more motor units may not be the exclusive explanation for the increased mean power frequencies in the more impaired arm. Additional factors, such as the presumed disuse of the more impaired arm, which may cause changes to the muscle structure (i.e., atrophy of muscle fibres and or increased distribution of type II muscle fibres), might contribute to the observed increase in mean power frequencies in the more impaired arm. This supports the notion that although SHCP has a neural origin, with the primary lesion being in the central nervous system, significant structural changes may occur to the skeletal muscle, which are secondary to the lesion (Pontén et al., 2005). In summary, the characteristics of muscle properties in children with SHCP, which affects motor behaviour, seem to be the result of a complex interaction between primary neurological and secondary behavioural factors.

In addition to determining the underlying neuromuscular activation of the upper limbs in children with SHCP during a symmetrical circular bimanual task, the effect of available visual information from the more and less impaired arm on motor behaviour was investigated under three visual conditions (i.e., glass, opaque screen and mirror). The manipulation of visual information, unlike the TD children, affected the temporal movement variability in children with SHCP, which was significantly greater in the screen condition compared to the glass and mirror condition. This suggests that providing children with SHCP with the opportunity to see a mirror reflection of their less impaired arm resulted in levels of temporal movement variability similar to that when performing in the glass condition. The important point to note is that while no beneficial effects of the mirror were found, there were also no negative effects of substituting the veridical information from the more impaired limb with a mirror reflection of the less impaired limb. However, EMG intensities in the shoulder muscles of children with SHCP were lower when the mirror was in place compared to the other visual manipulations, especially the glass condition. Similar attenuating effects of the mirror were found for the relative durations of eccentric and concentric activity in the elbow muscles. The manipulation of visual information did not affect the neuromuscular activation in TD children to the same extent as children with SHCP. Based on these observations it may be hypothesized that a discrepancy between the actual visual feedback and internal efference copy, may contribute to the motor difficulties in children with SHCP. Combined with the kinematic results, these results suggest that removing actual visual information of the more impaired arm and replacing it with a mirror reflection of the less impaired arm seems to improve the motor behaviour of children with SHCP during interlimb coupling more than the other conditions.

Some caution is warranted when interpreting the results of the studies in this thesis. The participants in the studies were homogeneous in the sense of having SHCP, they were undoubtedly heterogeneous in terms of pathology (i.e., location, size and timing of the unilateral insults to the brain). The relatively small number of participants with SHCP in the respective studies is inadequate to compare the effect of pathology on motor behaviour during visual manipulation. More importantly, most of the pathological data was unknown or unavailable. Furthermore, the studies in this thesis were designed to gain insight into the contribution of visual information towards interlimb coupling in children with and without SHCP. However, the additional pathological data would have enhanced the interpretation of the findings and aid the understanding of the underlying mechanisms. Previous research provided evidence that the capacity for the corticospinal pathways to reorganise depends on the extent and timing of the brain lesion (Staudt et al., 2000; 2002; 2004), which, in turn, might influence the bimanual coordination in children with SHCP when visual information is manipulated. Despite the large amount of variability, significant effects were still found for the 'mirror box', which might tentatively suggest that the effects are independent from the pathology of the brain lesion in children with a mild form of SHCP. Furthermore, the studies have yielded an important initial insight into the effects of visual information during bimanual coordination in children with SHCP. However, to gain a more comprehensive insight in to the effect of the 'mirror box' illusion on motor behaviour, future studies should attempt to investigate the extent of the unilateral brain insult in children with SHCP and its effect on bimanual coordination when visual information is manipulated. This research is essential to investigate which individuals with SHCP are more likely to respond to 'mirror box' therapy and to understand the underlying mechanisms.

**Future directions**

The experiments in this thesis were part of a first stage in the development of the 'mirror box' as a rehabilitation device for children with SHCP. Based on the positive results found in these experiments, future research is warranted to investigate if long-term clinical interventions with the 'mirror box' have similar effects on bimanual coordination and neuromuscular activity. If this is indeed the case, a third phase of research should be conducted to establish if the beneficial effects on bimanual coordination and neuromuscular activity found in the 'mirror box', transfer to other daily life activities. For instance, improved motor behaviour in the more impaired arm during interlimb coupling may transfer to the skill of walking, as there is a close link between arm movement and balance in locomotion (Ledebt et al., 2005; Ledebt, 2000). Furthermore, questions regarding fundamental issues on the development of movement coordination in children with and without SHCP still remain unanswered, which will be discussed in the following sections.

*Contribution of vision and/or proprioception*

The inclusion of typically developed adults and more TD children in smaller age-ranges in Chapter 2, which investigated the bimanual coordination and neuromuscular activity in TD children, would have afforded the opportunity to trace the developmental changes in motor behaviour and contribution of visual and/or proprioceptive feedback from (young) childhood via adolescents to adulthood. Furthermore, in this thesis (Chapter 2) it was suggested that visual feedback might contribute predominantly towards the spatial coupling between the arms, whereas proprioceptive information monitors the temporal component of bimanual coordination. To investigate this further, future experiments should incorporate a circle drawing task, which is not constrained to a fixed circle diameter. Additionally, it was proposed that future research should examine the effects of distorted proprioceptive information on the temporal aspects of a continuous bimanual circle drawing task. In Chapter 3 it was shown that children with SHCP, who have limitations in proprioceptive feedback from the more affected extremities (Van Der Weel et al., 1995), had higher levels of temporal variability in the screen condition. The consistent interlimb temporal coupling and neuromuscular activation in the TD children during the different visual conditions seems to be attributed to the interchangeable contribution of visual and proprioceptive feedback. However, an interesting question related to fundamental research would be: Do children with and without SHCP monitor the visual and proprioceptive information constantly or intermittently during the performance of bimanual coordination?

A possible way to investigate the contribution from afferent signals would be to replace the changeable divide in the experimental set-up, described in Chapter 2, with a flat-screen monitor. When participants trace a pre-recorded circular arm movement projected on the monitor with both arms on either side of the monitor, the pre-recorded arm becomes a superimposed image of the contralateral arm, which is occluded from view behind the monitor. The proposed experimental protocol may consist of at least two conditions where the pre-recorded arm movement frequency (i.e., movement time) remains constant at low movement frequency and progressively accelerates with discrete steps. The assumption is that in order for the children to successfully trace the pre-recorded arm at higher movement frequencies, an intermittent monitoring of the feedback is required, because the latency period of afferent signals to the central nervous system is too long for a constant monitoring to contribute towards interlimb coupling. The relevance to examine this question in future work is that if the monitoring of afferent signals is better understood during interlimb coupling, a more refined intervention with the ‘mirror box’ can be designed.

*Oculomotor function*

In a complex task such as driving, it was found that eye movements and steering (i.e., arm movements) are tightly linked and that without this optimal coordination, driving was impaired (Marple-Horvat et al., 2005). Moreover, it was found that motion of the eyes (i.e., looking across to the inside of the kerb) itself benefited steering, even when the eye movements did not yield the visual information sought (i.e., the inside of the kerb was occluded from view; Wilson et al., 2007). In children with SHCP the movements of the more impaired arm are jerky and, therefore, if there is a tight link between eye and arm movements, the jerky movements of the more impaired arm may affect the motion of the eye. In turn, this might lead to a further deterioration of the motor behaviour of the arms. The placement of a mirror between the arms of children with SHCP removes the visual feedback of the more impaired arm and replaces it with a mirror reflection of the less impaired arm. The movement of the less impaired arm seen in the mirror reflection is less jerky than the actual movements of the more impaired arm and it has to be examined whether this has a beneficial effect on the motion of the eyes. The effects of the mirror on eye and arm movements can be investigated with an eye-tracker. Furthermore, to investigate the hypothesis of a tight link between eye and arm movements further, the reflective side of the mirror can be turned towards the more impaired arm. Effectively, the visual feedback of the less impaired arm is then replaced with a mirror reflection of the more impaired arm. If there is a tight link between eye and arm movements, the effect of seeing two more impaired arms is assumed to increase the jerky movements of the eyes, which is predicted to have a detrimental effect on the motor behaviour of the arms during interlimb coupling.

*Neuroimaging*

It has been recognized that changes in motor behaviour during rehabilitation are a consequence of plasticity in the central nervous system (Ramachandran, 2005). The hypotheses of the different corticospinal pathways proposed by Yarosh et al. (2004) the results from Staudt and colleagues' work (2000; 2002; 2004), demonstrating the relationship between the corticospinal tract reorganisation and the pathology of hemiparesis, have been previously discussed. Future research should establish the relationship between the origin and nature of the pathology and potential behavioural effects of 'mirror box' training and examine if cortical reorganisation occurs in children with SHCP during a prolonged training protocol with the 'mirror box'. Similar research techniques to those used by Staudt and co-workers (2000; 2002; 2004) could be utilized. For instance, the functional integrity of crossed cortico-spinal projections in the affected brain hemisphere, as well as the presence of any ipsilateral projections to the more impaired arm, could be examined by TMS. Furthermore, fMRI may be a more appropriate method to investigate if changes in the cortical activation have occurred after a prolonged period of clinical intervention with the 'mirror box'.

*Muscle properties*

The difference in mean power frequency in the majority of muscles between the more impaired arm compared to the less impaired arm reflected the asymmetric nature of SHCP. The results in Chapter 4 suggest that structural changes occur because of a complex interaction between the clinical characteristics of SHCP and external factors. However, the linear correlation between mean power frequency and structural muscle properties is based on simplified models, which are not directly related to functional movement. The research in this thesis has highlighted that future work should be directed towards the investigation of the relationship between mean power frequency and muscle fibre type distribution in vivo. The work is essential because if a direct relationship can be shown, the mean power frequency might be a useful parameter to evaluate the effectiveness of an intervention targeted at manipulating muscle structure (Wakeling et al., 2007; Kupa et al., 1995). Moreover, the measurement of mean power frequency to investigate muscle fibre type distribution could stretch far beyond rehabilitation. For instance, the measurement technique could be used to identify morphological phenotypes that will be beneficial towards certain (Olympic) sports. This might help to scout for (young) individuals who are more suited towards a sport discipline that requires more sprint or endurance aspects.

**Implications for therapeutic interventions**

Changes in muscle structure properties in children with SHCP have important implications with respect to the nature of therapeutic interventions. A recent trend has occurred in rehabilitation therapy to subject children with SHCP to resistance training (Roeleveld et al., 2008), which aims to increase the strength capacity of the weakened muscles (Wiley & Damiano, 1998). The muscle fibre type distribution is plastic and frequent exposure to short periods of high intensive (i.e., resistance) activation increases the percentage of type II fibres in the muscles (Lieber et al., 2004; Bear et al., 2001). Although an increase in muscle strength capacity might facilitate the children during daily life activities, children with SHCP were found to have muscles or activate motor units with a large distribution of type II muscle fibres (Chapter 4). Moreover, the resistance training might increase the type II fibre distribution, which could cause the adverse effect of a quicker onset of muscular fatigue. Subjecting children with SHCP to long periods of low intensive activation (i.e., endurance therapy) might increase the percentage of type I muscle fibres, which delays the onset of fatigue. Therefore, the important point to note is that clinicians should consider incorporating exercises into there rehabilitation protocols, which aim to increase both muscular strength and endurance because both aspects of the muscle state contribute to daily life activities.

Current practice to improve functional movement of children with SHCP generally aims to reduce the hyperactivity of the stretch reflex and/or tonus activity in the muscles of the more affected arm with tendon lengthening and botulinum toxin injections. These interventions can cause the patient high levels of distress. The experiments in this thesis (Chapter 3 and 5) showed that the manipulation of visual information has the potential to improve motor behaviour. Specifically, the results showed that the ‘mirror box’ illusion enables children with a mild form of SHCP to temporally couple their upper limbs during bimanual movements tighter and conjunctively reduce the neuromuscular activity. Although the ‘mirror box’ is not a cure for SHCP and has not been investigated in children with severe forms of SHCP, the results from this thesis suggest that targeted rehabilitation of arm movement with the ‘mirror box’ might provide clinicians at least with a method to prevent and/or manage the movement difficulties encountered by children with a mild form of SHCP, and make surgical intervention, such as tendon lengthening, only necessary in very severe cases.

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# Samenvatting

Kinderen met SHCP vertonen als gevolg van unilaterale hersenschade verhoogde spiertonus in bepaalde spiergroepen aan de contralaterale zijde van het lichaam. Dit kan onder andere leiden tot een abnormale rekreflex (Miller, 2005) en draagt bij tot de spastische en schokkerige bewegingen van de aangedane ledenmaten (Steenbergen et al., 2008; Wakeling et al., 2007; Perry et al., 2001; Ikeda et al., 1998). Als gevolg van deze motorische problemen ondervinden kinderen met SHCP duidelijke moeilijkheden bij het uitvoeren van dagdagelijkse actvititeiten, zeker wanneer dit de coördinatie van beide ledematen vergt. Eerder onderzoek naar de controle en coördinatie van bimanuele taken toonde aan de kwaliteit van de bewegingen van de meer aangedane arm positief beïnvloed kan worden door simultane bewegingen van de minder aangedane arm (Steenbergen et al., 2008; Utley et al., 2004). Mogelijk wordt deze aanpassing veroorzaakt door een natuurlijke neiging om de bewegingsduur, –uitslag en –richting tussen de armen te synchroniseren (Cauraugh & Summers, 2005).

Voorheen werd gedacht dat de 1:1 ratio tussen de bewegingen van de armen vast lag in de motorische sturing, mogelijk door de anatomische structuur en organisatie van het zenuwstelsel. Echter, met behulp van een ingenieus experiment liet Mechsner et al. (2001) zien dat volwassen gemakkelijk hele complexe bimanuele bewegingspatronen konden uitvoeren (vb. ratios van 4:3, 3:2 en 2:1) wanneer de visuele informatie zo werd gemanipuleerd dat de beweging tussen de armen een 1:1 ratio leek te hebben. Dit bewijst dat ook visuele informatie invloed heeft op bimanuele coördinatie. Daarnaast toonden klinische studies aan dat manipulatie van de visuele feedback, meer bepaald door de visuele informatie van de aangedane arm te vervangen door het spiegelbeeld van de minder aangedane arm, bevorderlijk is voor het functioneren van de meer aangedane arm in volwassenen met unilaterale bewegingsstoornissen (Ramachandran et al., 1995; Altschuler et al., 1999). Op basis hiervan werd verondersteld dat dergelijke manipulaties van visuele informatie ook een positieve invloed hebben op de bimanuele coördinatie van andere klinische populaties met unilaterale stoornissen, zoals kinderen met SHCP. De algemene doelstelling van dit proefschrift was daarom het bepalen van de rol van visuele informatie op de koppeling van de twee armen en de daarmee gepaard gaande spieractiviteit (EMG) tijdens een symmetrische bimanuele cirkeltaak in kinderen met en zonder spastische hemiparetisch cerebrale parese (SHCP). Meerbepaald werd nagegaan of gespiegelde visuele informatie van de niet aangedane arm de kwaliteit van de coördinatie tussen de armen en de beweging van de meer aangedane arm kon verbeteren. De invloed van visuele informatie op bimanuele coördinatie in kinderen met SHCP (leeftijd 8 – 18 jaar) werd getest door middel van drie manipulaties: (1) de plaatsing van een glazen afscheiding, (2) een ondoorschijnend scherm of (3) een spiegel (‘mirror box’) tussen de armen. Hierdoor was visuele feedback beschikbaar van beide armen (glas-conditie), van enkel de minder aangedane arm (scherm-conditie), of van de minder aangedane arm en het spiegelbeeld daarvan (spiegel-conditie). Wanneer, in de laatste conditie, de de minder aangedane arm aan de spiegelzijde een beweging maakte, zorgde dit voor een visuele illusie waarbij de arm aan de andere zijde schijnbaar dezelfde beweging uitvoerde. De symmetrische cirkeltaak bestond uit het rondraaien van twee schijven in een horizontaal vlak in een 1:1 patroon (m.a.w. de rechterhand ging tegen de klok in terwijl de linkerhand met de klok mee bewoog). De mate van synchronisatie van beide armbewegingen en de variabiliteit hiervan werden gemeten aan de hand van het gemiddelde en de standaarddeviatie van de continue relatieve fase tussen de armen. Daarnaast werd de hoeveelheid en aard van spieractiviteit bilateraal bepaald op basis van de EMG-signalen en de relatieve duur van de soort spieractiviteit (concentrisch, excentrisch en isometrisch) in de flexoren en extensoren van de pols, elleboog en schouder.

Om de bevindingen met betrekking tot bimanuele coördinatie tijdens deze specifieke taak bij kinderen met SHCP beter te begrijpen, werd in **hoofdstuk 2** onderzocht hoe de verschillende kinematische en neuromusculaire aspecten en de invloed van visuele informatie bij een dergelijke taak veranderden tijdens een normale ontwikkeling. Er werd gevonden dat een groep jongere typisch ontwikkelende kinderen (leeftijd 5 – 10 jaar) gemiddeld eenzelfde 1:1 ratio coördinatiepatroon (gemiddelde continue relatieve fase en bewegingsduur) kon handhaven als de oudere leeftijdsgroep (leeftijd 12 – 18 jaar). Echter, de variabiliteit van het neergezette patroon (standaarddeviatie continue relatieve fase) bij de jongere kinderen was groter. In deze groep ging de beweging ook gepaard met een hogere spieractiviteit in vier van de zes gemeten spieren. Dit wijst op een mogelijke associatie tussen het verbeteren van de stabiliteit van een synchrone cirkelbeweging en een daling van de neuromusculaire activiteit tijdens de ontwikkeling. Hoofdstuk 2 liet ook zien dat zowel bij de jongere als de oudere kinderen, de manipulatie van visuele informatie geen invloed had op de synchroniciteit van het bewegingspatroon of de gemiddelde spieractiviteit. Dit suggereert dus dat de bijdrage van visuele informatie tijdens deze bimanuele cirkeltaak verwisselbaar was met proprioceptieve informatie.

In **hoofdstuk 3** werd de invloed van visuele manipulatie op kinematische aspecten tijdens het uitvoeren van een symmetrische bimanuele cirkeltaak bij kinderen met SHCP vergeleken met een controlepopulatie**.** Kinderen met SHCP konden eenzelfde gemiddeld in fase coördinatiepatroon handhaven maar met grotere bewegingsvariatie tijdens de bimanuele cirkelbeweging in vergelijking met een typische ontwikkelde controlegroep. Bovendien bleek dat de variabiliteit van het bewegingspatroon van kinderen met SHCP significant groter was in de scherm-conditie in vergelijking met de glas- en spiegel-conditie, die een gelijkaardige variabiliteit vertoonden. Deze bevindingen suggereren dat kinderen met SHCP moeilijkheden hebben om stabiel een bewegingspatroon te handhaven wanneer visuele informatie van de meer aangedane arm afwezig is. Echter, wanneer een spiegelbeeld van de minder aangedane arm wordt aangeboden, blijkt de coördinatie te stabiliseren tot het niveau van de glas-conditie.

In **hoofdstuk 4** werd de hoeveelheid en aard van spieractiviteit bij kinderen met en zonder SHCP onderzocht tijdens het uitvoeren van een symmetrische bimanuele cirkeltaak. Typisch ontwikkelende kinderen hadden minder spieractiviteit in de armen nodig voor het uitvoeren van deze specifieke taak in vergelijking met de kinderen met SHCP. Een opvallende bevinding was dat de waarden voor de gemiddelde EMG-intensiteit van de spieren in de aangedane en niet-aangedane arm vergelijkbaar waren. Dit suggereert dat de spieractivatie van de armen bilateraal gekoppeld is, ondanks de unilaterale hersenschade. Daarnaast werd de beweging van kinderen met SHCP gekarakteriseerd door langere fasen van concentrische en excentrische activiteit, vooral in de aangedane arm. Dit geeft aan dat meer activatie en co-activatie nodig was om de bimanuele cirkeltaak uit te voeren. Powerspectrum-analyse van de EMG-signalen liet een hogere “mean power frequency” zien in alle spieren van de meer aangedane arm en de pols- en elleboogflexoren van de minder aangedane arm van de kinderen met SHCP. Dit wijst erop dat er in deze kinderen relatief meer type II spiervezels werden ingeschakeld in vergelijking met typische ontwikkelende kinderen. Samengevat toont deze studie aan dat de effecten van SHCP niet alleen bijdragen tot veranderingen in spieractivitatie, maar potentieel ook leiden tot veranderingen van de spierstructuur.

In **hoofdstuk 5** werd de invloed van visuele manipulatie op neuromusculaire aspecten van de symmetrische bimanuele cirkeltaak bij kinderen met en zonder SHCP onderzocht en vergeleken. Kinderen met SHCP hadden minder neuromusculaire activiteit nodig in de schouderspieren wanneer de werkelijke visuele informatie van de meer aangedane arm afwezig was (d.i. in de scherm- en spiegel-conditie). Een bevinding in dezelfde lijn was dat de beweging van kinderen met SHCP gekarakteriseerd werd door kortere fasen van concentrische en excentrische activiteit in de elleboogspieren tijdens de spiegel-conditie. Deze bevindingen suggereren dat de manipulatie van visuele informatie invloed heeft op de neuromusculaire aspecten van de beweging tijdens het uitvoeren van een symmetrische bimanuele cirkeltaak. Dit zou er kunnen op wijzen dat de unilaterale bewegingsaandoeningen die kinderen met SHCP ervaren niet enkel het gevolg zijn van structurele beschadiging van het centraal zenuwstelsel of verhoogde spiertonus, maar dat ook visuele informatie van de meer aangedane arm een belangrijke rol speelt.

De bevindingen uit deze studies laten zien dat de bimanuele coördinatie bij kinderen met SHCP stabieler is wanneer, tijdens de symmetrische cirkelbeweging, visuele informatie beschikbaar is van de twee armen, ongeacht de aard van de informatie (d.i. de ‘echte’ arm of de gespiegelde minder aangedane arm). Daarnaast blijkt dat de symmetrische cirkelbeweging wordt gerealiseerd met minder (co-)activatie wanneer visuele informatie van de meer aangedane arm gemaskeerd is. Op basis van de kinematische en de neuromusculaire resultaten kan samengesteld worden dat de spiegel-conditie leidt tot het meest gunstige bewegingspatroon. Een mogelijke verklaring voor dit effect ligt in de hypothese dat het afstemmen en corrigeren van visuele feedback van de beweging van de meer aangedane arm (afferente visuele feedback) op de geplande beweging (efferente kopie) door middel van een spiegelbeeld van de minder aangedane arm, de motorische outflow naar de meer aangedane (gedeeltelijk) herstelt (Ramachandran, 2005).

Op basis van de resultaten van de studies beschreven in dit proefschrift kan geconcludeerd worden dat het acuut vervangen van reële visuele informatie van de meer aangedane arm met een spiegelbeeld van de minder aangedane arm, een positief effect lijkt te hebben op de bimanuele cirkeltaak en de daarmee gepaard gaande spieractiviteit in kinderen met SHCP. Fundamenteel vervolgonderzoek zal moeten nagaan welke concrete neurofysiologische en –psychologische mechanismen ten grondslag liggen aan deze effecten, maar de bevindingen openen alvast perspectieven voor een nieuw soort interventie ter bevordering van de armfunctie van kinderen met SHCP. Klinisch onderzoek moet vaststellen of deze effecten na een langere periode van 'spiegeltherapie' versterkt worden en of ze ook overgedragen worden op andere bewegingen. Beide vormen van onderzoek zijn noodzakelijk om de volle betekenis van de effecten te begrijpen en uit te buiten.

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*Or walk with kings - nor lose the common touch,*
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*Yours is the Earth and everything that's in it,*
*And - which is more - you'll be a Man, my son!*
If - Rudyard Kipling (1865-1936)

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# Appendix

| Modified Ashworth Scale | |
|---|---|
| 0 | No increase in muscle tone |
| 1 | Slight increase in muscle tone, manifested by a catch and release or minimal resistance at the end of the range of movement (ROM) when affected part is moved in flexion or extension. |
| 1+ | Slight increase in muscle tone, manifested by a catch followed by minimal resistance throughout the remainder (less than half) of the ROM. |
| 2 | More marked in crease in muscle tone through most of the ROM, but affected part easily moved. |
| 3 | Considerable increase in muscle tone, passive movement difficult. |
| 4 | Affected parts rigid in flexion and extension. |

| WeeFIM | | | | |
|---|---|---|---|---|
| Motor Items | Self-Care | A | Eating | |
| | | B | Grooming | |
| | | C | Bathing | |
| | | D | Dressing - upper body | |
| | | E | Dressing - lower body | |
| | | F | Toileting | |
| | Sphincter control | G | Bladder management | |
| | | H | Bowel management | |
| | Transfer | I | Bed/chair, wheelchair | |
| | | J | Toilet | |
| | | K | Tub | |
| | Locomotion | L | Walk/wheelchair | |
| | | M | Stairs | |
| Cognitive Items | Communication | N | Comprehension | |
| | | O | Expression | |
| | Social cognition | P | Social interaction | |
| | | Q | Problem solving | |
| | | R | Memory | |
| Level of Scoring | Independent | | 7 - Complete independenc (timely, safely)<br>6 - Modified independence (device) | |
| | Modified dependence | | 5 - Supervision<br>4 - Minimal assistance (subject 75%+)<br>3 - Moderate assistance (subject 50%+) | |
| | Complete dependence | | 2 - Maximal assistance (subject 25% +)<br>1 - Total assistance (subject 0% +) | |

GMFCS taken from CanChild (with permission).

# Gross Motor Function Classification System for Cerebral Palsy

Robert Palisano, Peter Rosenbaum, Stephen Walter, Dianne Russell, Ellen Wood, Barbara Galuppi

## Introduction & User Instructions

The Gross Motor Function Classification System for cerebral palsy is based on self-initiated movement with particular emphasis on sitting (truncal control) and walking. When defining a 5 level Classification System, our primary criterion was that the distinctions in motor function between levels must be clinically meaningful. Distinctions between levels of motor function are based on functional limitations, the need for assistive technology, including mobility devices (such as walkers, crutches, and canes) and wheeled mobility, and to much lesser extent quality of movement. Level I includes children with neuromotor impairments whose functional limitations are less than what is typically associated with cerebral palsy, and children who have traditionally been diagnosed as having "minimal brain dysfunction" or "cerebral palsy of minimal severity". The distinctions between Levels I and II therefore are not as pronounced as the distinctions between the other Levels, particularly for infants less than 2 years of age.

The focus is on determining which level best represents the child's present abilities and limitations in motor function. Emphasis is on the child's usual performance in home, school, and community settings. It is therefore important to classify on ordinary performance (not best capacity), and not to include judgments about prognosis. Remember the purpose is to classify a child's present gross motor function, not to judge quality of movement or potential for improvement.

The descriptions of the 5 levels are broad and are not intended to describe all aspects of the function of individual children. For example, an infant with hemiplegia who is unable to crawl on hands and knees, but otherwise fits the description of Level I, would be classified in Level I. The scale is ordinal, with no intent that the distances between levels be considered equal or that children with cerebral palsy are equally distributed among the 5 levels. A summary of the distinctions between each pair of levels is provided to assist in determining the level that most closely resembles a child's current gross motor function.

The title for each level represents the highest level of mobility that a child is expected to achieve between 6-12 years of age. We recognize that classification of motor function is dependent on age, especially during infancy and early childhood. For each level, therefore, separate descriptions are provided for children in several age bands. The functional abilities and limitations for each age interval are intended to serve as guidelines, are not comprehensive, and are not norms. Children below age 2 should be considered at their corrected age if they were premature.

An effort has been made to emphasize children's function rather than their limitations. Thus as a general principle, the gross motor function of children who are able to perform the functions described in any particular level will probably be classified at or above that level; in contrast the gross motor functions of children who cannot perform the functions of a particular level will likely be classified below that level.

# Gross Motor Function Classification System for Cerebral Palsy (GMFCS)

## Before 2nd Birthday

Level I Infants move in and out of sitting and floor sit with both hands free to manipulate objects. Infants crawl on hands and knees, pull to stand and take steps holding on to furniture. Infants walk between 18 months and 2 years of age without the need for any assistive mobility device.

Level II Infants maintain floor sitting but may need to use their hands for support to maintain balance. Infants creep on their stomach or crawl on hands and knees. Infants may pull to stand and take steps holding on to furniture.

Level III Infants maintain floor sitting when the low back is supported. Infants roll and creep forward on their stomachs.

Level IV Infants have head control but trunk support is required for floor sitting. Infants can roll to supine and may roll to prone.

Level V Physical impairments limit voluntary control of movement. Infants are unable to maintain antigravity head and trunk postures in prone and sitting. Infants require adult assistance to roll.

## Between 2nd and 4th Birthday

Level I Children floor sit with both hands free to manipulate objects. Movements in and out of floor sitting and standing are performed without adult assistance. Children walk as the preferred method of mobility without the need for any assistive mobility device.

Level II Children floor sit but may have difficulty with balance when both hands are free to manipulate objects. Movements in and out of sitting are performed without adult assistance. Children pull to stand on a stable surface. Children crawl on hands and knees with a reciprocal pattern, cruise holding onto furniture and walk using an assistive mobility device as preferred methods of mobility

Level III Children maintain floor sitting often by "W-sitting" (sitting between flexed and internally rotated hips and knees) and may require adult assistance to assume sitting. Children creep on their stomach or crawl on hands and knees (often without reciprocal leg movements) as their primary methods of self-mobility. Children may pull to stand on a stable surface and cruise short distances. Children may walk short distances indoors using an assistive mobility device and adult assistance for steering and turning.

Level IV Children floor sit when placed, but are unable to maintain alignment and balance without use of their hands for support. Children frequently require adaptive equipment for sitting and standing. Self-mobility for short distances (within a room) is achieved through rolling, creeping on stomach, or crawling on hands and knees without reciprocal leg movement.

Level V Physical impairments restrict voluntary control of movement and the ability to maintain antigravity head and trunk postures. All areas of motor function are limited. Functional limitations in sitting and standing are not fully compensated for through the use of adaptive equipment and assistive technology. At Level V, children have no means of independent mobility and are transported. Some children achieve self-mobility using a power wheelchair with extensive adaptations.

## Between 4th and 6th Birthday

Level I Children get into and out of, and sit in, a chair without the need for hand support. Children move from the floor and from chair sitting to standing without the need for objects for support. Children walk indoors and outdoors, and climb stairs. Emerging ability to run and jump.

Level II Children sit in a chair with both hands free to manipulate objects. Children move from the floor to standing and from chair sitting to standing but often require a stable surface to push or pull up on with their arms. Children walk without the need for any assistive mobility device indoors and for short distances on level surfaces outdoors. Children climb stairs holding onto a railing but are unable to run or jump.

Level III Children sit on a regular chair but may require pelvic or trunk support to maximize hand function. Children move in and out of chair sitting using a stable surface to push on or pull up with their arms. Children walk with an assistive mobility device on level surfaces and climb stairs with assistance from an adult. Children frequently are transported when travelling for long distances or outdoors on uneven terrain.

Level IV Children sit on a chair but need adaptive seating for trunk control and to maximize hand function. Children move in and out of chair sitting with assistance from an adult or a stable surface to push or pull up on with their arms. Children may at best walk short distances with a walker and adult supervision but have difficulty turning and maintaining balance on uneven surfaces. Children are transported in the community. Children may achieve self-mobility using a power wheelchair.

Level V — Physical impairments restrict voluntary control of movement and the ability to maintain antigravity head and trunk postures. All areas of motor function are limited. Functional limitations in sitting and standing are not fully compensated for through the use of adaptive equipment and assistive technology. At Level V, children have no means of independent mobility and are transported. Some children achieve self-mobility using a power wheelchair with extensive adaptations.

**Between 6th and 12th Birthday**

Level I — Children walk indoors and outdoors, and climb stairs without limitations. Children perform gross motor skills including running and jumping but speed, balance, and coordination are reduced.

Level II — Children walk indoors and outdoors, and climb stairs holding onto a railing but experience limitations walking on uneven surfaces and inclines, and walking in crowds or confined spaces. Children have at best only minimal ability to perform gross motor skills such as running and jumping.

Level III — Children walk indoors or outdoors on a level surface with an assistive mobility device. Children may climb stairs holding onto a railing. Depending on upper limb function, children propel a wheelchair manually or are transported when travelling for long distances or outdoors on uneven terrain.

Level IV — Children may maintain levels of function achieved before age 6 or rely more on wheeled mobility at home, school, and in the community. Children may achieve self-mobility using a power wheelchair.

Level V — Physical impairments restrict voluntary control of movement and the ability to maintain antigravity head and trunk postures. All areas of motor function are limited. Functional limitations in sitting and standing are not fully compensated for through the use of adaptive equipment and assistive technology. At level V, children have no means of independent mobility and are transported. Some children achieve self-mobility using a power wheelchair with extensive adaptations.

**Distinctions Between Levels I and II**

Compared with children in Level I, children in Level II have limitations in the ease of performing movement transitions; walking outdoors and in the community; the need for assistive mobility devices when beginning to walk; quality of movement; and the ability to perform gross motor skills such as running and jumping.

**Distinctions Between Levels II and III**

Differences are seen in the degree of achievement of functional mobility. Children in Level III need assistive mobility devices and frequently orthoses to walk, while children in Level II do not require assistive mobility devices after age 4.

**Distinctions Between Level III and IV**

Differences in sitting ability and mobility exist, even allowing for extensive use of assistive technology. Children in Level III sit independently, have independent floor mobility, and walk with assistive mobility devices. Children in Level IV function in sitting (usually supported) but independent mobility is very limited. Children in Level IV are more likely to be transported or use power mobility.

**Distinctions Between Levels IV and V**

Children in Level V lack independence even in basic antigravity postural control. Self-mobility is achieved only if the child can learn how to operate an electrically powered wheelchair.

## Original Reference

Palisano, R., Rosenbaum, P., Walter, S., Russell, D., Wood, E., & Galuppi, B. (1997). Development and reliability of a system to classify gross motor function in children with cerebral palsy. *Developmental Medicine & Child Neurology, 39*, 214-223.

**Toestemmingsformulier** **Amsterdam, 6 oktober 2006**

**(Informed Consent)**

Ik verklaar hierbij op voor mij duidelijke wijze, mondeling en schriftelijk, te zijn ingelicht over de aard en belasting van het onderzoek. Mijn vragen zijn naar tevredenheid beantwoord. De schriftelijke informatie, behorend bij deze verklaring, is mij overhandigd.

Ik stem geheel vrijwillig in met deelname van mijn kind aan dit onderzoek. Ik behoud daarbij het recht deze instemming weer in te trekken zonder dat ik daarvoor een reden behoef op te geven.

Naam ouder / voogd: ………………………………………….

…………………(datum) ……………………………………… (handtekening)

Naam kind …………………………………………………..

…………………(datum) ……………………………………… (handtekening)

Ik heb mondelinge en schriftelijke toelichten verstrekt op het onderzoek. Ik verklaar mij bereid nog opkomende vragen over het onderzoek naar vermogen te beantwoorden.

Een eventuele voortijdige beëindiging van deelname aan dit onderzoek zal niet van invloed zijn op de behandeling.

Naam onderzoek:……………………………………………..

Naam onderzoeker:……………………………………………

…………………(datum) ………………………………(handtekening onderzoeker)

**Vragenlijst bij onderzoek:**

**(Research Questionnaire)**

Zou u deze vragenlijst zo volledig mogelijk ingevuld mee willen nemen met het toestemmingsformulier? De gegevens worden anoniem verwerkt.

<u>Contactinformatie:</u>

Telefoonnummer: : …………………………

Eventueel email-adres : …………………………

<u>Algemene infromatie over het kind:</u>

Initialen : …………………………

Roepnaam : …………………………

Sekse : …………………………

Geboortedatum : ………/………/………..

Lichaamslengte : …………………………

Voorkeurshand : links / rechts / geen voorkeur

Welk soort onderwijs volgt uw kind?

regulier / mytylschool / tyltylschool / anders, nl: …………………………

<u>Informatie over de aandoening:</u>

Type CP : hemiplegie / diplegie

(Meest) aangedane zijde : links / rechts

Mate van de aandoening : licht / gemiddeld / zwaar

Oorzaak van de CP, indien bekend:

..............................................................................................................................

..............................................................................................................................

Is er sprake van spasticiteit, zo ja, in welke ledematen en in welke mate?

..............................................................................................................................

..............................................................................................................................

Andere informatie over de aandoening op dit moment, zoals bewegingsbeperkingen, spierkracht, etc:

.............................................................................................................................

.............................................................................................................................

Uitgevoerde operaties gerelateerd aan de CP:

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Gebruikte medicijnen gerelateerd aan de CP:

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.............................................................................................................................

Gebruikte hulpmiddelen gerelateerd aan de CP:

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.............................................................................................................................

Huidige behandelingen en fysiotherapie:

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.............................................................................................................................

Fysiotherapeut :..........................................................................................

Telefoonnummer :..........................................................................................

<u>Testuitslagen van veel uitgevoerde tests bij kinderen met CP</u>

Voor zover ze (bij u) bekend zijn, met daarbij de datum waarop die score vastgesteld is. Eventueel navragen bij uw behandelend fysiotherapeut.

Ashworth score :……………………………………………… Datum: …/…/….

GMFM score :……………………………………………… Datum: …/…/….

GMFCS score :……………………………………………… Datum: …/…/….

Hartelijk dank voor het invullen van deze vragenlijst! Als u nog opmerkingen of toevoegingen heeft hunt u die hieronder kwijt: